Master Thesis

Development of an Atmosphere Management System for Bio-regenerative Life Support Systems

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Aachen, 23. September 2014

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Topic

Future, long duration manned missions to the Moon or Mars are only feasible through the use of local resources or by producing commodities on site. A solution for on-site production of commodities is the use of greenhouse modules.

Greenhouse modules are often considered for space-based life support systems as they can be utilized for food and oxygen production, CO_2 reduction, waste water recycling and general waste management. Plants are cultivated by using so called CEA (Controlled Environment Agriculture) technologies. To further investigate CEA technologies, especially for space application, the DLR Institute of Space Systems established the EDEN (Evolution and Design of an Environmentally-closed Nutrition source) research group and laboratory. A critical aspect of this laboratory is the Atmosphere Management System (AMS), which is responsible for providing suitable air temperature, air velocity, humidity and CO_2 concentration.

The objective of this Master thesis is the development of a preliminary design of the AMS. The development of the AMS must respect existing laboratory interfaces and requirements associated with future laboratory enhancements and research group objectives.

Figure 1: Evolution and design of an environmentally-closed nutrition source (EDEN) Group- Logo

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Summary

The objective of this Master thesis is the development of a concept for controlling the humidity, temperature and ambient CO_2 concentration in a greenhouse module. A primary goal is to retrieve the extracted water from the air for recycling and thereby ensure durable operation of the system. To achieve this, research first focused on the primary AMS objectives and requirements. A brief introduction to plant physiology is given. Analyzing the connection and boundary conditions a function diagram of the system is derived. Working principles for the sub functions are developed. The working principles are critically evaluated in the next step and a feasible overall concept is selected. The concept is divided into a modular system and the components are designed and control-software is set up. A design of all subsystems is the outcome of this phase. After this, the realization of the final concept is illustrated in a prototype. The manufactured solution was tested and critically evaluated to provide lessons learned for further iterations. The result of this thesis is a prototype of the AMS which fulfills the requirements and provides a continuous control of humidity, temperature and CO_2 level inside the plant growth chambers.

Zusammenfassung

Das Ziel dieser Masterarbeit ist die Entwicklung eines Konzeptes zur Steuerung der Luftfeuchtigkeit, Temperatur und des CO_2 Gehalts in einem Gewächshausmodul. Hauptaugenmerk soll dabei auf die Wasserrückgewinnung und einen wartungsarmen Betrieb gelegt werden. Zur Erreichung der Ziele werden zu Beginn Grundlagen der Pflanzenphyiologie erwähnt und im Anschluss die Anforderungen an das System festgelegt. Im Rahmen eines Top-Down Prozesses wird eine Funktionsstruktur erstellt und das System bis auf Ebene der Elementarfunktionen analysiert. Aufbauend auf der Analyse werden mehrere Konzepte für die verschiedenen Subsysteme vorgestellt und bewertet. Das beste Gesamtkonzept wird ausgewählt und in verschiedene zu realisierende Module gegliedert. Im nächsten Schritt werden die Module ausgestaltet und eine Kontrollsoftware wird erstellt. Das Gesamtkonzept wird im Anschluss anhand eines Technologiedemonstrators vorgestellt und getestet. Die Arbeit schließt mit Hinweisen für die Weiterentwicklung des Systems.

1 Introduction

1.1 Growing plants in the context of future space exploration

According to the global exploration roadmap, which was developed by the International Space Exploration Coordination Group (ISECG), two possible pathways for post International Space Station (ISS) exploration of space exist (ISECG 2011). The first one includes the exploration of a Near Earth Object (NEO) followed by a return to the moon and eventually a trip to Mars. The second pathway includes a return to the moon, then a NEO mission and then a subsequent trip to Mars (Figure 2). Automated greenhouses as an integrated part of future habitats are essential for sustaining the long term presence of humans in space in both of these exploration scenarios.

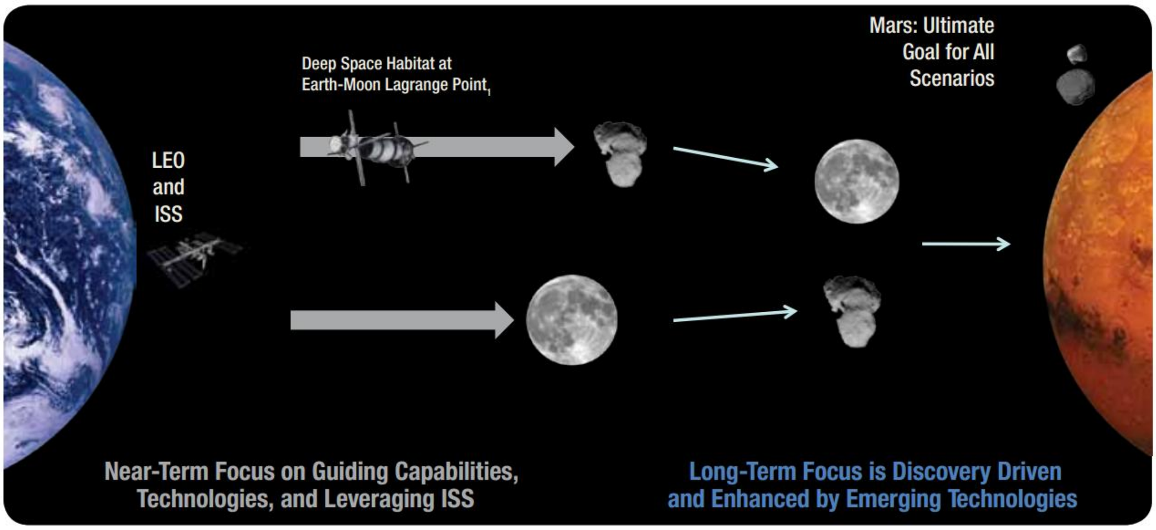


Figure 2: Optional exploration pathway scenario of the ISECG (Source: ISECG 2011)

Cultivating plants in habitats provides several benefits on long duration missions. Due to limited resources in space, life support systems consist of several loops such as the waste water recycling loop, the respiratory gas loop and others to recycle as many resources as possible. Today, some of these loops can be closed with little loss. Nevertheless, important loops, like the CO_2 / oxygen recycle and nutrient loop, are not yet fully closed. Food, as well as oxygen needs to be carried from Earth which, especially on long duration missions, increases the supply mass and hence the costs significantly (Figure 3). Also, growing plants in closed habitats has been observed to provide psychological benefits to participating crew members (Schlacht 2008).

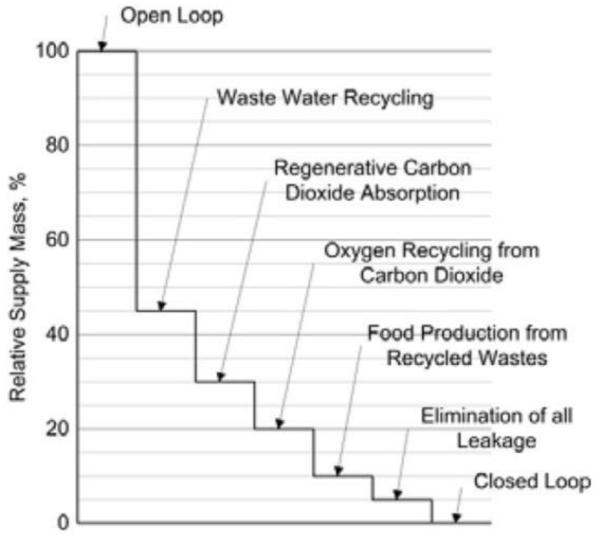


Figure 3: Savings in relative supply mass by closing different loops within a habitat (Source: Eckart 1994)

1.2 Structure of the development process and the master thesis

For the development of the Atmosphere Management System, the systematic approach as given by the VDI 2221 is chosen. It covers all phases of development for a new product and defines tasks and findings for each stage. Hence, the structure of this thesis is compliant with the VDI 2221.

Chapter two of this thesis explains the project fundamentals and motivation. It introduces the current status of the DLR greenhouse activities as well as some basic knowledge about plant physiology. Based on the introduction, the task is clarified and the requirement list is set up in chapter three. Chapter four covers the conceptual design phase. The function structure, principle solutions and several concepts for the components of the AMS are designed in this chapter. The system synthesis in chapter five focuses on gathering and evaluating the found principle solutions regarding their interdependencies. The outcome of this chapter is an overall concept. The embodiment design of the key modules in boundaries given by the requirement list is described in chapter six. Also, the prototype setup is described here. The chapter finishes with a discussion of the solution and gives hints for further iterations. The conclusion in chapter seven summarizes the solution in connection with the initial task formulation.

2 Project fundamentals

2.1 EDEN initiative

The focus of the DLR research initiative 'EDEN' (Evolution and Design of an Environmentally-closed Nutrition source) is on the development and evaluation of Controlled Environmental Agriculture (CEA) technologies towards future space-based and remote terrestrial greenhouse design. The greenhouse module is supposed to provide high performance fresh food production and to participate in the cycles of bio-regenerative life support system in planetary space habitats (Schubert 2011). The DLR Institute of Space Systems launched the EDEN research initiative in 2011.

Space habitation plant laboratory

The laboratory was founded in April 2013. It attempts to provide a test-bed for the basic mechanical design for a planetary self-contained growing supply of nutritional fruit and vegetables. Current CEA technologies are installed and reviewed in the laboratory. However, new CEA technologies are also developed. Identified agricultural subsystems are the germination unit, the cleaning-in-place and sterilization-in-place unit, the food quality assurance unit, the aeroponic/hydroponic distribution and irrigation system, the plant growth unit, the health monitoring system, the harvest- and work area, the storage unit, the mix computer unit (for the nutrient solution), the fluid storage and quality control unit (Schubert 2013).

Analogue test site

For further testing of the developed technologies and to prove the concept of a modular greenhouse in a remote location, a greenhouse module inside a 40 foot container is planned for end of 2014. The greenhouse module shall be deployed at the German Neumayer Station III, which is located in the Antarctic, for supplying the crew with fresh vegetables. It is necessary to develop the CEA technologies in the laboratory with strong prospect to the analogue test site to reduce the necessary effort for customization.

2.2 Greenhouse test facilities

Numerous greenhouse test facilities are already installed around the world. Table 1 gives a short overview of test facilities and feasibility studies that focus on the development of future space-based greenhouse modules. The Biomass Production Chamber (BPC) which was located at the Kennedy Space Center focused on analyzing mass/energy flow, hardware selection and crop selection/crop parameter investigation. The Micro-Ecological Life Support System Alternative (MELiSSA) project was started by ESA in 1988 to investigate the possibility of recycling edible biomass from waste, CO_2 and minerals using light as a source of energy to promote photosynthesis. The Amundsen-Scott South Pole Food Growth chamber is an example of a greenhouse module designed to provide humans in a remote area with fresh vegetables. The Lada experiment on the ISS focusses on plant growth under microgravity. Solving the health issues of the plant is a major research goal. Plant leaves are frozen and carried to Earth in order to analyze the nutritional value and bacterial counts to investigate food safety. Additionally, the psychological influence of plants on the crew is a research topic. The Lunar Food and Air Revitalization Module is the result of a feasibility study to design a permanent human exploration base on the lunar surface. In general, one can say that there is a high level of interest in environmentally closed greenhouse modules for future long duration space missions or for the supply of food in remote areas.

Table 1: Selected greenhouse test facilities (Schubert 2013)

Name	Biomass Production Chamber (BPC)	MELiSSA Pilot Plant Higher Plant Chamber (HPC)	Amundsen-Scott South Pole Food Growth Chamber	LADA	Lunar Food and Air Revitalization Module (FARM)
Facility					
Timeframe	1988 – 1996	2009 - current	2004 – current	2002 - current	n/a
Type of facility	Ground-based terrestrial test chamber	MELiSSA HPC Prototype	Antarctic greenhouse	ISS Experiment	Lunar Greenhouse Concept
Organization	NASA KSC	University of Guelph, Universita Autonoma de Barcelona (UAB), ESA	University of Arizona, United States Antarctic Program	Space Dynamics Lab, Utah State University (USU), and Moscow IBMP	International Master SEEDS
GHM architecture	Upright cylindrical two-stories walk-in growth chamber	Rectangular reach-in growth chamber	Rectangular walk-in growth chamber	Small growth chamber	Rigid cylindrical structure

Cultivation Method	Hydroponics	Hydroponics (thin nutrient film technique)	Hydroponics	Granulated, non-oxidized clay enriched with a long duration time-release fertilizer	Hydroponics
Lights	HPS	HPS and MH	HPS	Fluorescent lamps (to be replaced by LEDs in 2013)	Indirect sunlight; HPS
Human isolation	No	No	Yes	Yes	n/a
Research focus	Provides a unique opportunity to learn about the mass and energy flow though the CELSS along with the environmental needs for plant growth in a concealed environment. Grow accommodation analysis	Provides comprehensive test facility for ground demonstration of MELiSSA Higher Plant compartment.	Bioregenerative life support systems research along with food support for crew and other psychological benefits.	Plant growth in microgravity. Created to provide a "space garden" for astronauts during their long flights.	Designed as a plant growth chamber module to be integrated into bioregenerative life support systems for a lunar mission.
Mission duration	n/a (decommissioned)	n/a	8 months per year since 2004	ongoing	n/a
Location	Kennedy Space Center, USA	UAB, Spain	Antarctica	ISS	Moon
Crop selection	Lettuce, wheat, soybean, potato	Lettuce	Lettuce, cucumber, tomatoes, herbs, peppers, flowers, cantaloupe	Mizuna, tomatoes, peas, radishes, peppers, and rice.	Bean, Cabbage, Carrot, Lettuce, Onion, Strawberry, Rice, White Potato, etc.

2.3 Plant classification and the function of the stoma

Generally, plants can be divided in the C3 and C4 group, depending on their photosynthesis process. Most plants above 30° latitude are C3 plants (e.g. rice, wheat, vegetables, fruits), while most plants below 30° latitude are C4 plants (e.g. grass, corn, sugar cane). For the EDEN initiative, mostly C3 plants are of interest.

Photosynthesis is a bio-chemical process that converts CO_2 and water into sugar and oxygen using energy provided by light. The sugar is used for growth within the plant. In C4 plants, CO_2 is fixed in the mesophyll cells and then transported to bundle sheath cells where the conversion of CO_2 to sugar occurs. In C3 plants, the conversion of CO_2 to sugar happens in the same mesophyll cells. Plants interact directly with their environment. One important example is the interaction of a plants with the surrounding air which makes the control of the atmosphere in an environmentally closed module a highly dynamic process. Hence, it is important to understand the internal regulation of plants and their interfaces with the air in order to control the humidity and CO_2 concentration in an artificial environment. The function of the stomata is of particularly high relevance. The stoma is a pore, located at the epidermis of leaves, which enables gas- and water exchange with the surrounding air (Figure 4). The plant recognizes the amount of light, the light quality, the plant water status and the CO_2 concentration and changes the aperture of the stoma. An open stoma enables intake of CO_2 and oxygen and disposal of water through transpiration. A closed stoma stops the exchange. During night-time the stomata are closed due to the lack of ambient light.

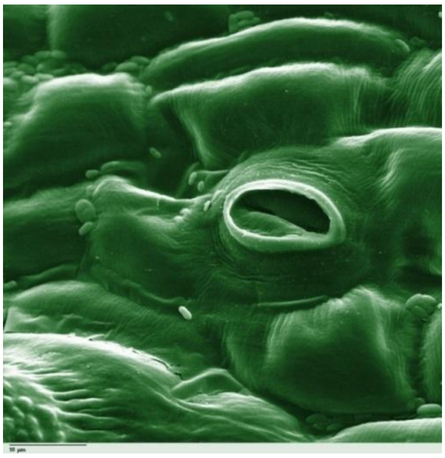


Figure 4: Scanning electron microscope image of *Lycopersicon esculentum* (Tomato) lower leaf surface, showing stoma and also some fungi attached to leaf surface (Source: Dartmouth)

2.4 Plant response to humidity in the surrounding air

The humidity of the air directly affects plant growth because it is influences the aperture of the stomata. The aperture of the stomata affects plants directly through the water transpiration rate and gas exchange and indirectly by modifying the plants energy balance and its physical and biological environment (Langhans 1997). The most important influence on humidity lies in the plant's transpiration rate. This means the amount of water the plant can evaporate through the stomata. Generally, the transpiration rate increases if the stomata of the plant are open which happens if humidity decreases in the surrounding air or the amount of CO_2 in the plant is low. However, the plant transpiration rate also depends on:

- Temperature difference (between the plant and the ambient environment)
- Irradiance
- Air movement
- Plant permeability to water vapour (stomata and cuticle)

- Plant and soil water status (availability of water for evaporation)
- Extent of evaporation surface and orientation
- Atmospheric pressure

The plants internal water status is dependent on the water absorption rate at the root and the water loss by transpiration. Generally, 99% of the water taken up by the roots is transpired through the leaves. So under steady state conditions, the water uptake through the roots per day under certain environmental conditions can be used to determine the amount of water which needs to be dehumidified.

2.5 Plant response to atmospheric CO_2 level

Besides sunlight and water CO_2 is the main compound associated with photosynthesis. The ambient CO_2 level in the outside air at sea level is around 340 ppm. An increased CO_2 level of 1000 ppm increases the photosynthesis rate of C3 plants in a proportional manner, which results in more reaction products and thus faster plant growth. For most C3 crops the saturation point will be reached at 1000–1300 ppm under ideal circumstances (Figure 5). A lower level (800–1000 ppm) is recommended for raising seedlings (tomatoes, cucumbers and peppers) as well as for lettuce production (Kaiser 1997). The saturation point depends on the aperture of the stomata. For example, the CO_2 saturation point is lower under low-light levels because of a small aperture setting.

Any actively growing crop in a tightly clad greenhouse with little or no ventilation can readily reduce the CO_2 level during the day to as low as 200 ppm (Blom 2002). As a countermeasure, a steady supply of outside air is recommended. In an environmentally closed greenhouse, CO_2 needs to be supplied by additional sources.

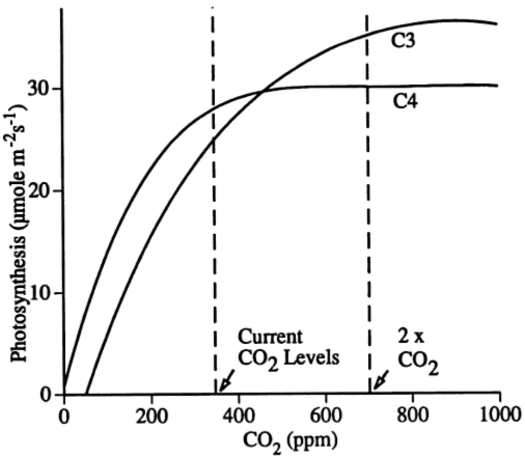


Figure 5: Response of photosynthesis to light of a C3/C4 plant (Kaiser 1997)

2.6 Control of air humidity and CO_2 concentration

As shown in previous chapters, optimal plant growth requires control of humidity, temperature and CO_2 concentration of the surrounding air. Another important point for controlling the atmosphere in greenhouses is the prevention of bacteria and fungus growth (Figure 6). Bacteria and fungi growth is a risk factor, since the spreading of diseases in closed modules may harm crops and may cause health issues to the consumer. Surface mold for example, was a major problem onboard the MIR Space Station (Ley 2009). To prevent this, certain humidity levels should not be surpassed and untreated standing water should be avoided.

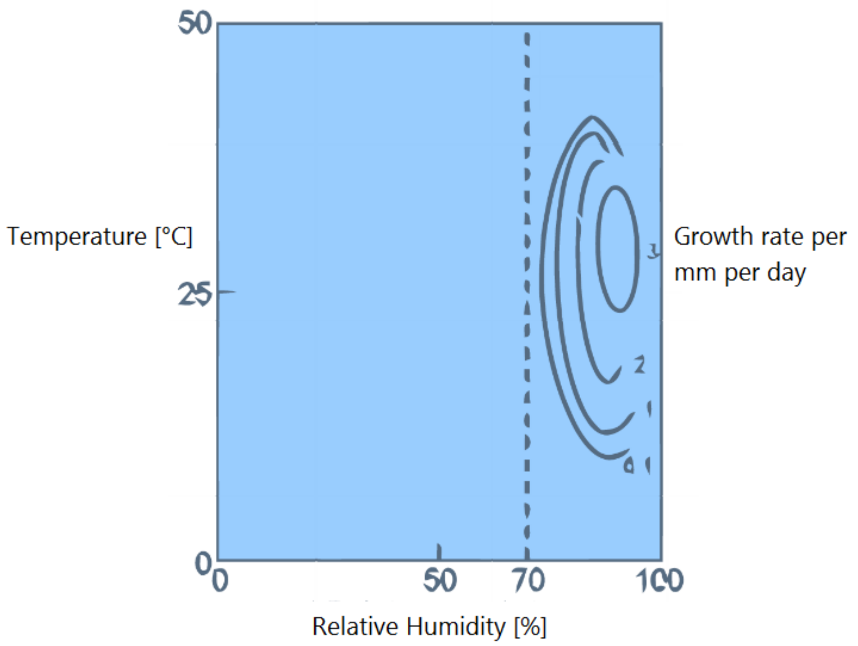


Figure 6: Fungus growth rate (Source: Munters)

Corrosion on metallic surfaces is another general problem that occurs with high humidity. Especially electronic parts need to be sealed carefully. Figure 7 shows exemplary the increase in weight on unalloyed steel due to corrosion caused by high humidity. While below a level of 40% relative humidity (RH), atmospherically induced corrosion is almost impossible, a proportional growth can be observed between 40% and 60-65% RH. Depending on the material and the contamination of air with pollutants, especially sulfur dioxide, corrosion rate will raise progressively with higher humidity. In unpolluted air, high humidity will result in a continuous proportional corrosion growth on unalloyed steel (Tostmann 2001).

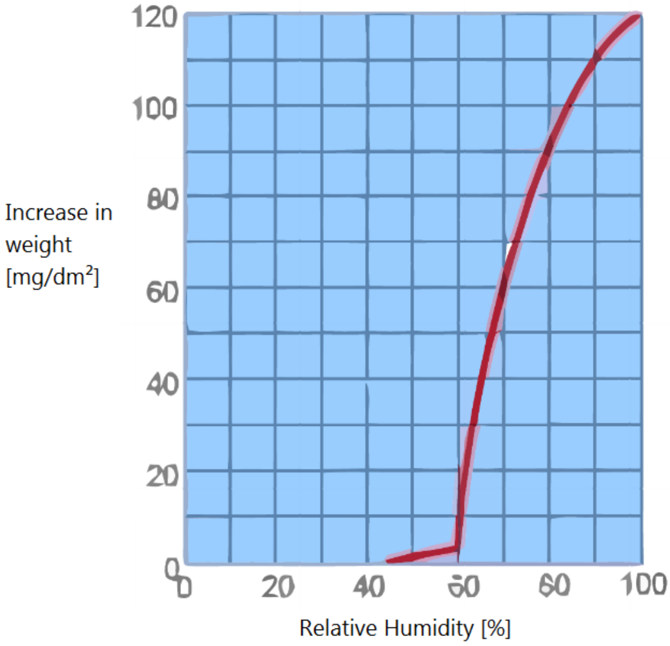


Figure 7: Increase in weight because of corrosion/relative humidity (Source: Munters)

In plant growth chambers, where 99% of the water uptake by the roots is transpired, water should not be wasted. So to close the loop within a life support system the water contained in the air should be retrieved for further use.

The injection of CO_2 is important because on the one hand, the plants reduce the amount of ambient CO_2. On the other hand, a high level of ambient CO_2 results under optimal circumstances in a faster growth and, therefore, in higher yield. The control of CO_2 is a prerequisite since a certain threshold of CO_2 should not be exceeded due to safety of the greenhouse users (Chapter 2.5).

2.7 State of the art solutions for greenhouse air management

Since greenhouse plant grow is widely used, a lot of different approaches already exist to control air humidity, temperature and CO_2 level. The institute of forest genetics in Hamburg-Grosshansdorf was visited on the 26th of November 2013 in order to gain information on state of the art greenhouse air management systems and operation procedures. The visited greenhouse (Figure 8) is typical for a commercially available greenhouse. The air humidity is controlled by opening and closing a ceiling vent. An open ceiling reduces the humidity in the greenhouse since the humidity caused by transpiration is significantly higher than the ambient humidity. In the unlikely case that the humidity is too low, water is sprayed manually on the floor. A humidity sensor is placed at plant-height. Heating coils with warm water are installed on both sides of the greenhouse and are activated if the temperature drops below a certain level. The CO_2 concentration is not controlled directly.

Figure 8: View inside the greenhouse of the institute of forest genetics in Hamburg-Grosshansdorf

Control takes place via several proportional control units (Figure 9). Control values are humidity, temperature and illuminance. The control of humidity and temperature is not time critical. As an example, the time for changing the temperature around 4 °C can take up to 30 minutes. Almost all greenhouses and climate chambers feature an exchange with outside air which is, in the case of a closed loop greenhouse module, not feasible.

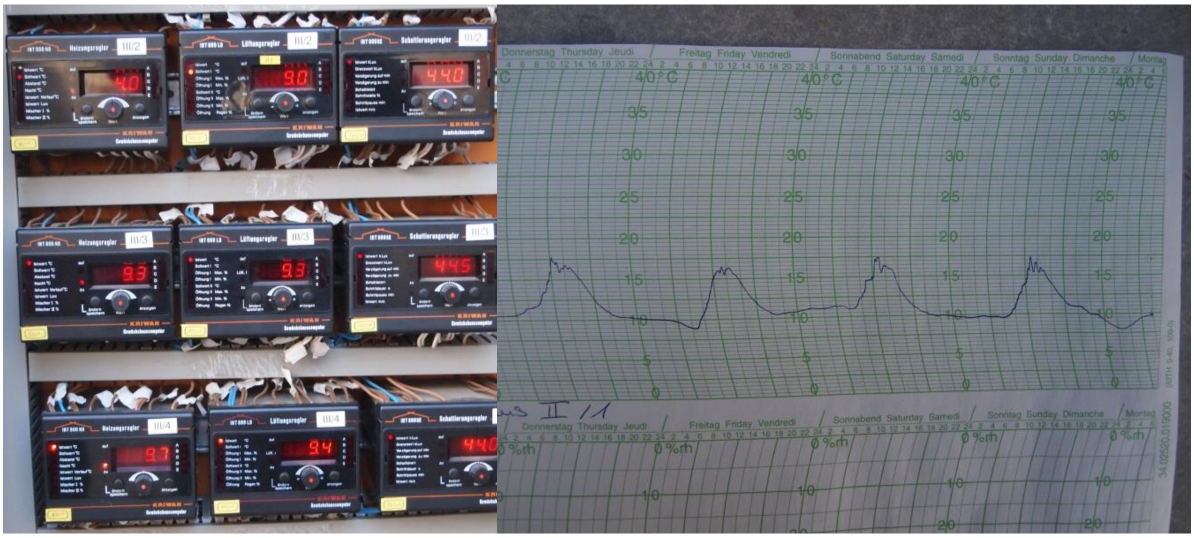


Figure 9: Control interface and typical temperature measurement over time

3 Task clarification and requirements definition

Since no preliminary design was made for the AMS of the EDEN Laboratory, the solution developed in this thesis is classified as a new development. The clarification of the task and the definition of requirements was therefore the first step in the development process. This chapter starts with a task setting which is abstracted from the initial assignment. In the next step, the requirements are developed using various sources. The outcome of this chapter is the requirements list.

3.1 Task setting

The main task of the project is to find a way to control the humidity and the CO_2 concentration inside the growth chambers within the EDEN Laboratory. A further aim is to prevent a fungus/bacteria friendly environment in the growth chambers and to retrieve the water extracted from the air for further use.

3.2 Boundary conditions

The AMS is a subsystem of the greenhouse module. Other systems are directly or indirectly connected to this subsystem. Figure 10 shows relevant subsystems that are directly connected. Nutrient enriched water from the nutrient delivery system is delivered to the plant roots via an aeroponic system. The water taken up by the plants is released to the air through plant transpiration. In the AMS, the water is extracted from the air and pumped to the osmosis machine for reconditioning. If the level of humidity is below the defined range, nutrient free water is used to increase the humidity. The conditioned air is enriched with CO_2 and vented to the growth chamber. The necessary air vents and water pipes, which are not shown explicitly in the figure, are also a fundamental part of the system.

However, other subsystems interfere with the AMS as well. The illumination control system provides the necessary lighting for the plants, which produce heat energy and thus changes the thermal characteristics of the air. The thermal control system is in charge of maintaining the greenhouse module temperature and providing respectively removing heat energy.

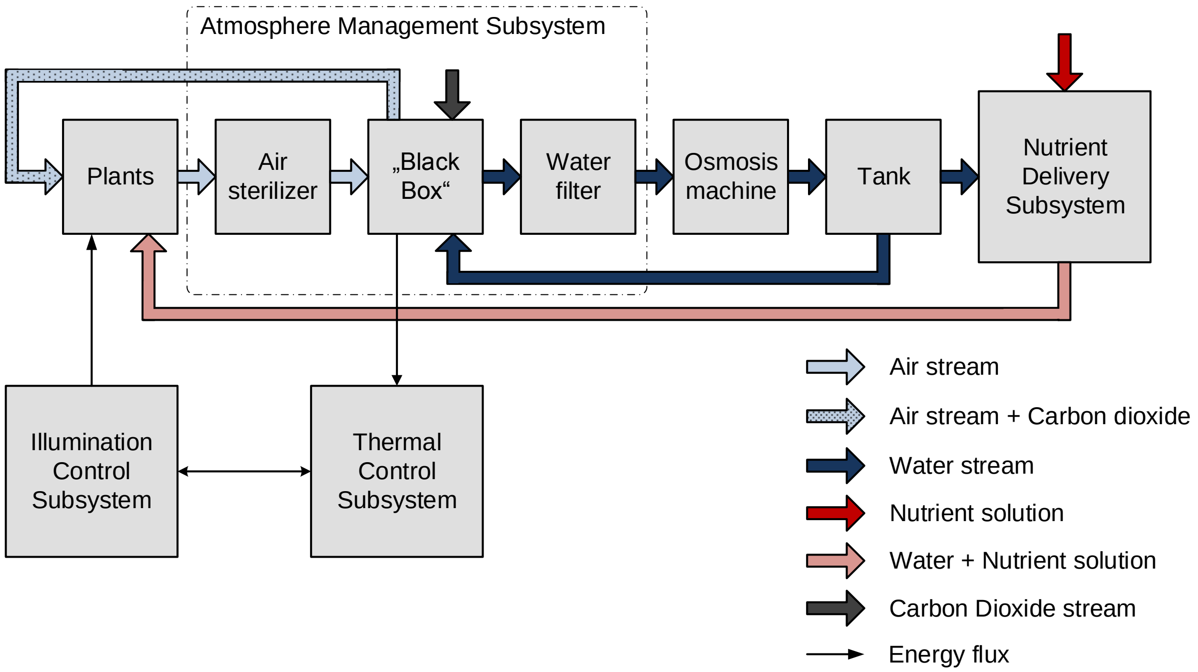


Figure 10: Embedment of the Atmosphere Management Subsystem in the EDEN Laboratory

This solution developed in this thesis should be implemented as the “Black Box” seen in Figure 10. The air sterilizer and water filter are not part of this thesis but suggestions regarding those are made in chapter 6.7.

3.3 Assessment of requirements

Initial technical requirements are stated in the Technical Note 104.1 of the “Greenhouse module for space systems” project led by the EDEN Initiative. The Technical Note 104.1 is the first technical note of the project and includes the working package 1300 “Review of Functional & Technical specifications”.

Additional requirements are discussed in expert meetings (16.10.2013 “Requirements Set up-discussion”). In particular, the requirements regarding geometry, safety and maintenance are developed with regard to a future deployment to an analogue test site.

A calculation tool was developed to predict the amount of daily produced water, the required CO_2 concentration of the plants and the estimated energy needed for processing the air. A realistic calculation for the laboratory is done in the following chapter. The calculator itself can be found in the digital appendix.

3.3.1 Estimation of the transpired water

The relative humidity is defined as the ratio between the partial pressure of water vapor in the mixture and the saturated vapor pressure of water at a given temperature. The pressure is temperature dependent as seen in Formula 1. The partial pressure of water vapor is hereby $\rho_{water\ vapour}$ and the saturated water vapor pressure is $\rho_{water\ vapour,\ max}$. The unit for both values is the Pascal.

$$\varphi = \frac{\rho_{water\ vapour}\ (T)}{\rho_{water\ vapour,\ max}\ (T)} * 100\%\ \ [\%] \tag{1}$$

The optimal relative humidity for plant growth is around 50-70%. A higher humidity decreases the ability of the plant to transpire water and decreases the growth rate. A lower humidity is technically difficult to achieve and does not benefit the growth rate. A relative humidity of lower than 25% should be avoided as it increases the risk of electrostatic charge and thus subsequent discharge sparking. It should also be avoided to prevent the user's mucous membranes from drying out (Ley 2009). Since the calculation of the water transpiration rate of the plants depends on many parameters, assumptions for average water production of several plants during the day are made (Hanford 2006). This reduces the calculation to a selection of the plants and the growth area. The crop area is defined by the growth chambers. Since the plants are going to be stacked on different levels inside the chamber, the base area needs to be multiplied by the number of racks (Formula 2). The total amount of crop area in the greenhouse module A_{total} is calculated in square meters as well as the crop area per stack per growth chamber, A_i.

$$A_{total} = \sum_{i=1}^{x} a_i * A_i\ \ [m^2] \tag{2}$$

The total crop area in the EDEN lab is calculated to 13.6 m^2. The total amount of water is calculated by multiplying the crop area with the water transpiration rate of tomatoes given by Hanford (2006) (Formula 3). The tomato plant was used because of its average water consumption (Zabel 2013 "Requirements Setup discussion"). The total amount of water transpired by plants, $\dot{m}_{Water}$, is given in kilograms per day and the average transpiration rate of the selected plant, µ, is given in kilograms per day per square meter. The total amount of crop area, A_{total}, is given in square meters.

$$\dot{m}_{Water} = \mu * A_{total}\ [\frac{kg}{d}] \tag{3}$$

The average amount of water transpired by tomato in the laboratory is calculated to 37.67 kg/d.

3.3.2 Estimation of CO_2 uptake

The optimal CO_2 concentration depends on the plant species, the time of the day and the safety of the users. If the CO_2 concentration is too low, photosynthesis does not take place. If no additional CO_2 source is applied to a closed loop greenhouse, the plants decrease the CO_2 concentration to a point where photosynthesis stops. For most plants, saturation is reached by 1000 – 1300 ppm (Chapter 2.5). Another factor for CO_2 concentration is the human user, since a concentration of 10000 ppm causes reduced mental control (Lambertsen 1971). The CO_2 uptake of the plants in the EDEN laboratory is calculated similar to the water transpiration. Here, the coefficient for average plant transpiration is substituted by the coefficient of average CO_2 uptake (Formula 4). The total amount of CO_2 uptake in kilogram by plants per day is $\dot{m}_{CO2}$, the average CO_2 uptake of the selected plant is γ and the total amount of crop area in the greenhouse module A_{total}.

$$\dot{m}_{CO2} = \frac{\gamma * A_{total}}{1000} \; [\frac{kg}{d}] \tag{4}$$

The total amount of CO_2 uptake by tomato plants on a surface area of 13,6 m^2 is calculated to 0,493 kg/d. Nevertheless, a higher ambient CO_2 concentration then 300ppm would also increase the CO_2 uptake as the photosynthesis rate increases. The CO_2 uptake using CO_2 fertilization will be determined in experiments once the injection system is installed.

3.3.3 Estimation of the necessary energy

The amount of energy for dehumidification is significantly higher than the amount of energy needed for the humidification or CO_2 injection. Consequently, they are neglected in the following calculation. The Mollier-h-x-diagram as seen in Figure 11 is used to estimate the necessary energy. The diagram combines temperature, specific enthalpy, relative humidity and the amount of water in wet air. Exemplary, data points for a hypothetic dehumidification process are set in the diagram. The wet air enters the dehumidifier with a temperature of 25 °C and a relative humidity of 80%, the upper right spot. The stream is cooled to a temperature of 7 °C which is below the dew point temperature of 21.4 °C and water starts condensing. As seen on the x-axis 9.4 g water per kg air condensates. The amount of water (m_{water}) per kilogram dry air (m_{dryair}) is defined in Formula 5.

$$x = \frac{m_{water}}{m_{dry\ air}} \left[\frac{g}{kg}\right] \quad (5)$$

The air mass stream is then heated to reach a temperature of 20 °C and 60% RH respectively. The total energy needed for heating and cooling is calculated by multiplying the total specific enthalpy with the air mass stream. The minimum air mass stream is calculated by dividing the total amount of water transpired by the plants per day by the amount of water per kg air at the desired temperature and relative humidity (Formula 6). The necessary air mass stream for dehumidification is given by $\dot{m}_{Air}$ and the total amount of water transpired by plants per day is given by $\dot{m}_{Water}$.

$$\dot{m}_{Air} = \frac{\dot{m}_{Water}}{x * 24} * 1000 \left[\frac{kg}{h}\right] \quad (6)$$

Multiplying the air mass stream with the specific enthalpy of the Mollier-diagram, 1.93 kW are calculated for cooling air to the desired temperature and 0.58 kW are needed for heating. So the total amount of energy needed is 2.51 kW. The values correlate with commercial available products (see Appendix: “Market research of commercial available Dehumidifiers”). Heat recovery is used in commercial products, which means that the heated cooling medium is used for preheating the cold airstream for creating a higher performance index.

A security factor of two is selected, leading to a power of around 4 kW for cooling and 1.3 kW for heating. The factor is necessary since the water transpiration of plants varies throughout the day and can reach peaks during phases of high illumination. Also the energy consumption is highly dependent on the temperature and the humidity ratio of the incoming air mass stream. At lower temperature and for dry air the energy consumption increases.

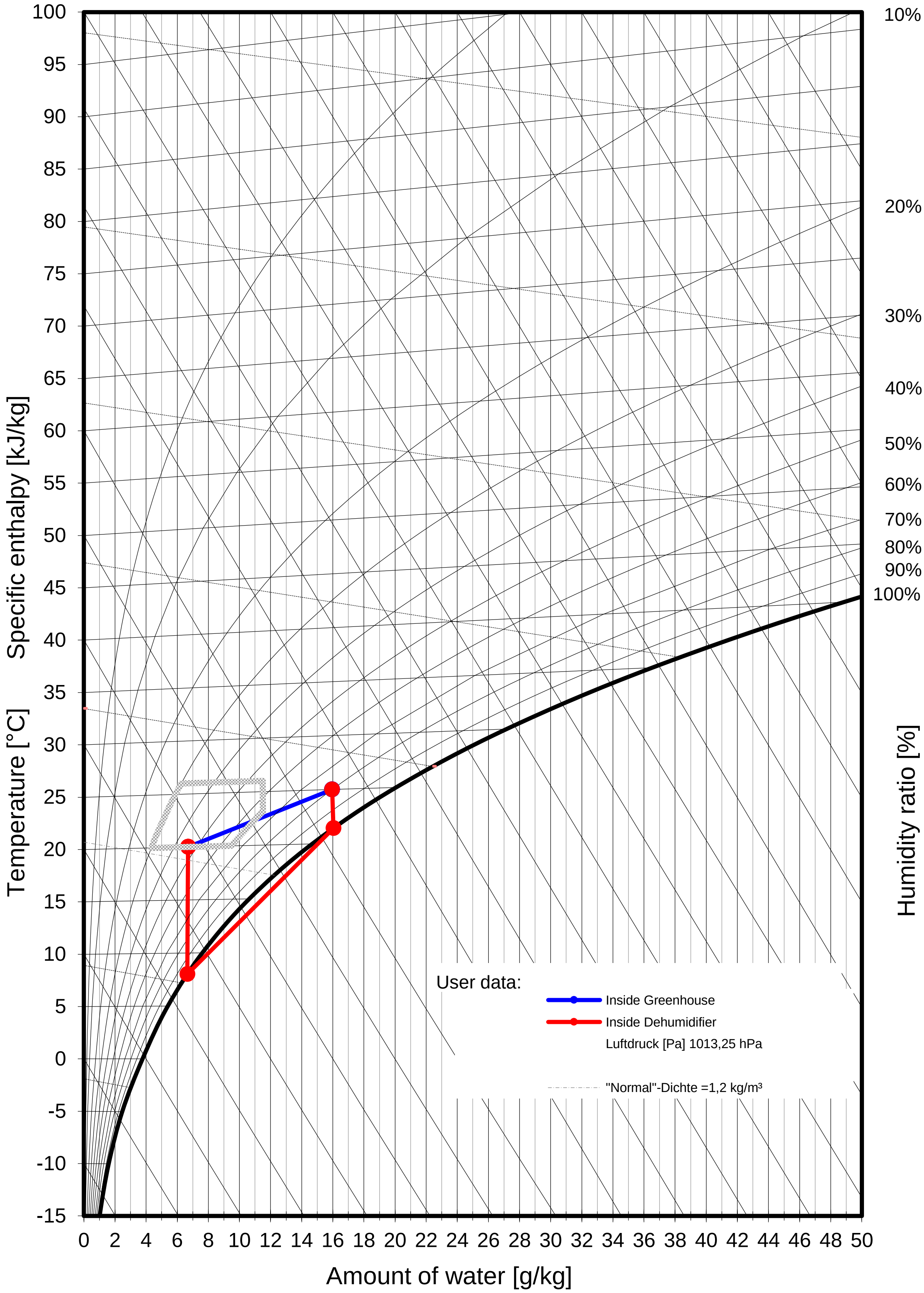


Figure 11: Mollier h-x-diagram with estimated greenhouse dehumidification process

3.4 Technology roadmap

The solution should be applied to the EDEN laboratory at DLR in Bremen. However, the near-term goal is a 40 foot high cube greenhouse container which is supposed to be sent to the Antarctic for a one-year analogue test (Figure 12). Hence, the solution developed in this master thesis should be primary designed for the greenhouse laboratory at the DLR with regard to the greenhouse container. The AMS is going to be integrated in the service section of the greenhouse container. The difference between the solution for the laboratory and the container is mainly a restriction in dimension and produced water, due to a difference in crop area. Furthermore, the container application requires longer maintenance intervals, which makes an almost sterile, maintenance free and redundant system necessary.

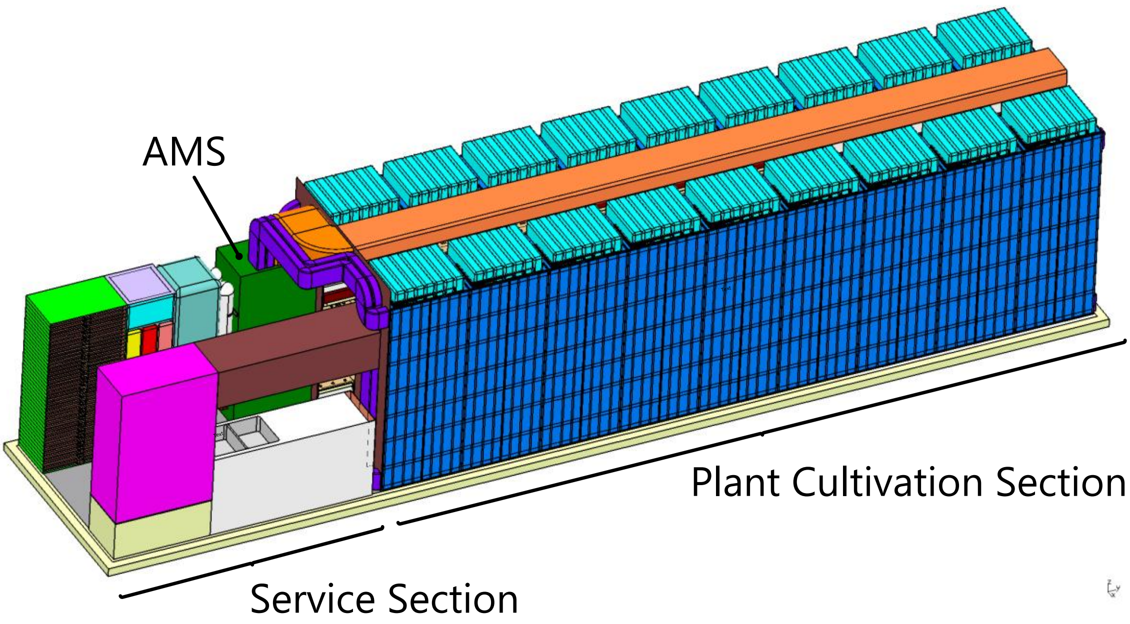


Figure 12: Concept drawing of a possible interior layout for greenhouse module to be deployed to an analogue test site (Source: Schubert 2012)

3.5 List of requirements

Table 2 shows the developed list of requirements. It is agreed with the project supervisors as the baseline for the further development. The first column indicates if the requirement is marked as a “wish” or a “demand”. Demanded requirements must be fulfilled while wished requirements are obligatory. The second and third columns name the requirements and boundary conditions. The fourth and fifth columns state who has setup the requirement and when it was compiled.

Table 2: List of requirements

Page: 1	List of Requirements Development of an Atmosphere Management System for Bio-regenerative Life Support Systems			
D/W	Requirement	Value	Responsible	Date
	Geometry			
D	Maximum Geometry (lenght x width x depth)	<2000x1500x600 mm	Zabel	16/10/2013
D	Connection to EDEN Lab Air conditioner		Zabel	16/10/2013
W	Connection to standardized piping adapter	DN 160 mm piping	Zabel	16/10/2013
	Greenhouse volume (EDEN Laboratory 2*5+4*0,5)	12 m^3	Kolvenbach	08/10/2013
	Predicted volume (Analogue test site 5*1,2*2,7)	16,2 m^3	Kolvenbach	08/10/2013
	Kinematics			
D	Maximum wind velocity inside the greenhouse	<0,5m/s	Zabel	16/10/2013
	Forces			
W	Excitation in natural frequency should be avoided		Zabel	16/10/2013
	Energy			
D	Input: Thermal energy (chilled water supply)	7 °C, 1,5 l/min, 5 kW	Kolvenbach	10/01/2014
D	Input: Electric energy	unlimited so far	Zabel	16/10/2013
	Material			
D	Input wet air Temperature	20-30 °C (+-0,5 °C)	Technical note 104.1	04/10/2013
D	Input wet air Humidity	(50-90 %) 60-90 %	Technical note 104.1	04/10/2013
D	Input water for Humidifier = Purified water		Schubert	13/11/2013
D	Input CO2 using connection to standard cylinders		Zabel	16/10/2013
D	Input wet air percentage of CO2	low percentage of CO2	Zabel	16/10/2013
D	Desired output air temperature	20-30 °C (+-0,5 °C)	Technical note 104.1	04/10/2013
D	Desired output wet air Humidity (non condensing)	50-85 % (+-5%)	Technical note 104.1	04/10/2013
D	Desired ambient CO2 level up to	1000 ppm (+- 50 ppm)	Zabel	16/10/2013
D	Removing/adding water vapor for the desired humidity		Technical note 104.1	04/10/2013
D	Plants used for humidity calculation	Tomato	Zabel	07/10/2013
D	Water dehumufication rate up to	70 kg/d	Kolvenbach	08/10/2013
D	Use of non corrosive materials		Zabel	16/10/2013
D	Avoiding fungus-friendly enviroment		Zabel	16/10/2013
D	Avoiding bacteria-friendly enviroment		Zabel	16/10/2013
	Signals			
D	Temperature, Humidity and CO2 control		Zabel	16/10/2013
D	Digital signal output for control (MATLAB, SPS, ...)		Zabel	16/10/2013
W	Data Visualization		Kolvenbach	16/10/2013
	Ergonomics			
W	Clarity of layout		Kolvenbach	16/10/2013
	Safety			
D	Malfunction report/alarm for critical CO2 concentration		Zabel	16/10/2013
D	Closing CO2 valve in case of critical concentration		Zabel	16/10/2013
D	Closing CO2 valve in case of power loss		Zabel	16/10/2013
D	Visualization of the CO2 Valve state using LEDs etc		Zabel	16/10/2013
	Operation			
D	Autonomous operation using feedback control systems		Zabel	16/10/2013
D	Quietness	Quiet	Technical note 104.1	16/10/2013
W	Modular design for Eden Lab with prospect to test site		Zabel	16/10/2013
	Maintenance			
D	Inspection rate	<1/month	Zabel	16/10/2013
W	Servicing interval rate	<1/year	Zabel	16/10/2013
D	Easy change of worn parts		Zabel	16/10/2013
	Costs			
W	Manufacturing costs around	≈2000 €	Zabel/Schubert	16/10/2013

4 Conceptual design

The conceptual design phase of a new product is defined as the phase in which different concepts are developed that fulfill the task within the boundaries of the requirements list

To achieve this, the task is abstracted and divided into sub functions to obtain a function structure of the system. According to VDI 2221, principle solutions are specified (Pahl 2007). The findings of this chapter are selected principle solutions for the sub functions of the function structure. In the next chapter, the modular systems are combined and evaluated in the system synthesis.

4.1 Function structure

The task is analyzed using the top down approach. Figure 10 already showed the implementation of the "Black Box" in a general overview. Investigations to sub-function level are described in this chapter.

Reasonable sub-functions are the air dehumidifier, the air humidifier and the CO_2 injection. Measuring devices for both, the relative humidity (including temperature) and the CO_2 concentration are necessary for control. A feedback control system for both processes is needed to close the control loop. Figure 13 shows the developed function structure. Mostly electric devices are colored red, software parts are colored green and the mechanical parts are colored grey. The wet air from the growing area enters the system border and is analyzed by the temperature, humidity and CO_2 sensor. Depending on these values and the desired values for humidity and CO_2 Concentration, a correction value is calculated. The dehumidifier or the humidifier can be activated in order to reach the desired humidity. The dehumidifier should extract water from the air and conduct it out of the system for post-processing. If the humidifier is activated, water from the osmosis machine shall be used to humidify the air. The CO_2 injection is activated if the sensed ambient CO_2 concentration is too low. The energy for fulfilling these tasks can be provided as heat energy or electrical energy.

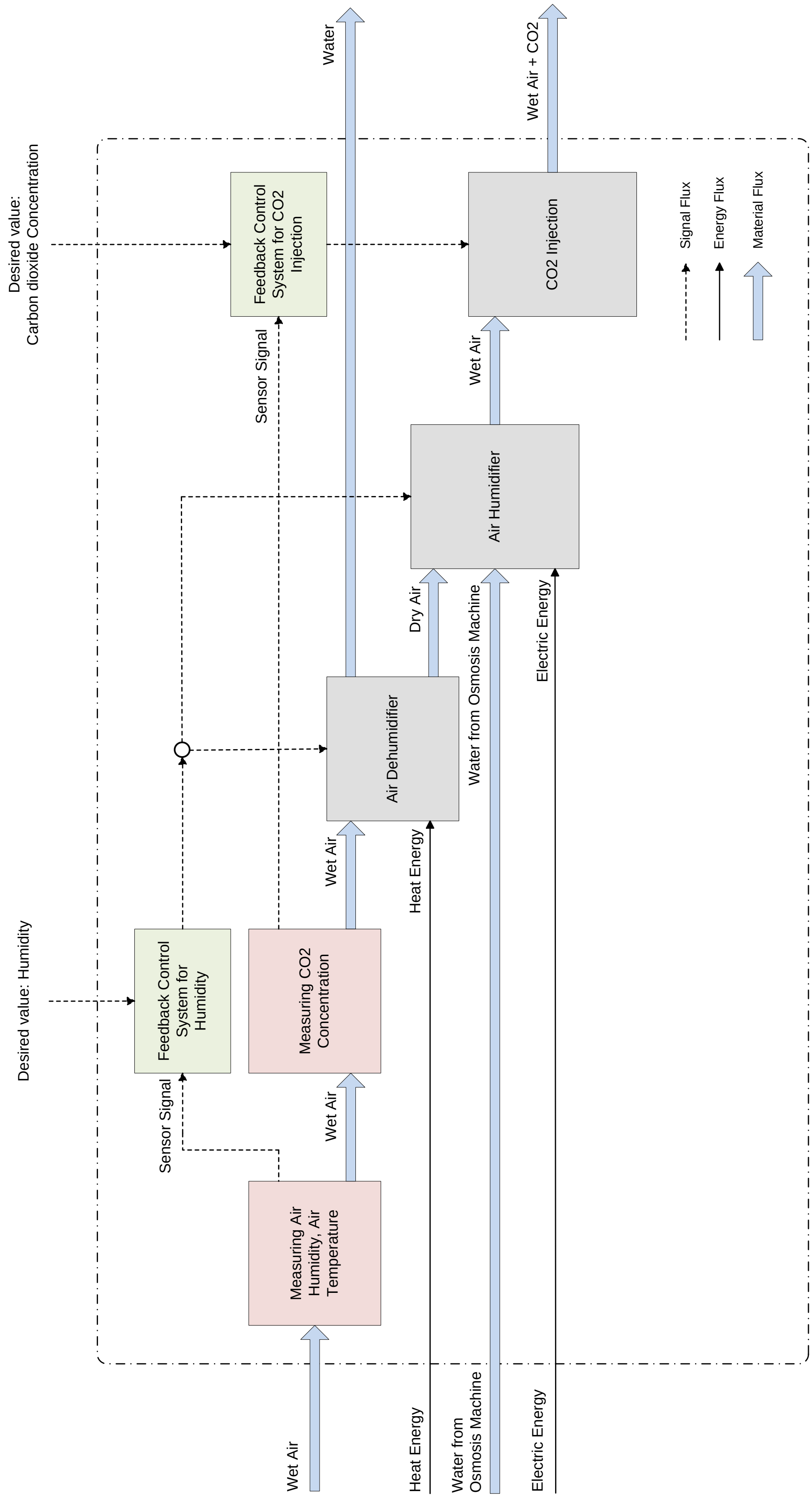


Figure 13: Function structure of the Atmosphere Management System

4.2 Generally valid function diagrams

For further analyzing the sub functions stated in the diagram, the generally valid functions are used. Various concepts can be generated for the sub function using the generally valid function diagram in combination with a physical effects table. Each function in the generally valid function diagram can be replaced with a physical effect of the working principle table (Table 3) to develop a unique concept. Even so, not every concept generated this way is feasible.

The generally valid function diagrams are developed for the dehumidifier, humidifier and CO_2 injection since these three functions are identified as the most important ones in terms of technical functionality and cost efficiency. A large number of concepts are requested in order to receive a large variety of viable solutions.

Generally valid function diagram for dehumidifier

Figure 14 shows the generally valid function diagram for the dehumidifier. A wet air mass stream enters the system border as well as an energy flux. The wet air stream is then separated into liquid water, which is conducted out of the system for further use.

If the air stream was cooled during the separating, it needs to be heated up to a certain level. In the next step the air needs to be accelerated and conducted out of the system. The energy gathering functions are realized by using energy which is split and converted into another form of energy. Nevertheless, different forms of energy supply can be realized.

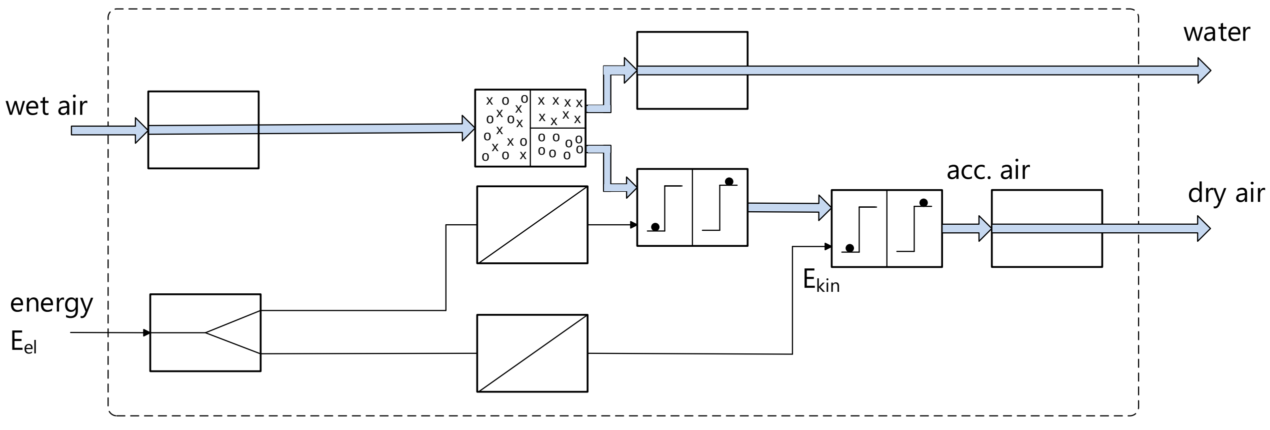


Figure 14: Generally valid function diagram for dehumidifier

Generally valid function diagram for humidifier

Figure 15 shows the generally valid function diagram for the humidifier. An air mass stream enters the system border as well as a purified water stream and an electric energy flux. The purified water is mixed with the air mass stream. To spread the humid air evenly inside the growth chamber, the wet air mass stream needs to be accelerated and conducted out of the system. To accelerate the air, the electric energy is converted into mechanical energy.

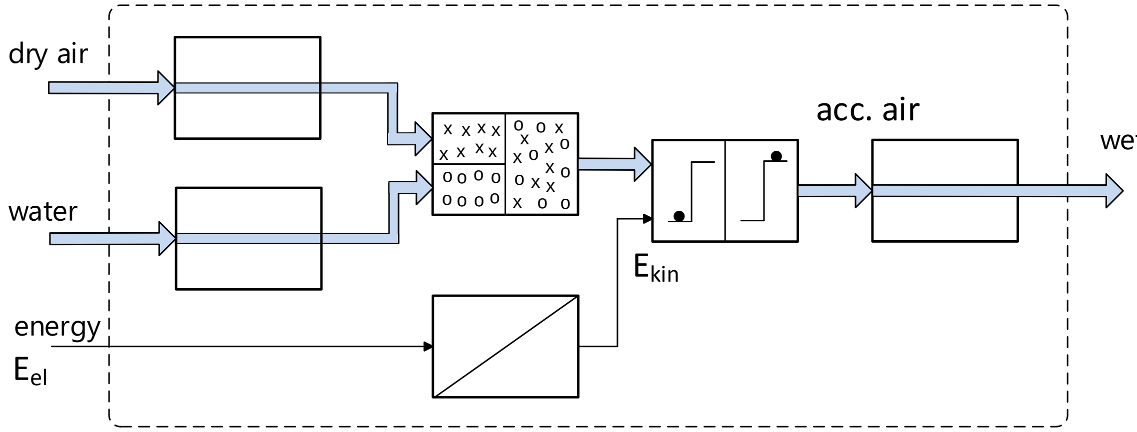


Figure 15: Generally valid function diagram for Humidifier

Generally valid function diagram for CO_2 injection

Figure 16 shows the generally valid function diagram for the CO_2 injection. CO_2 is stored isolated within the system and mixed with the air mass stream. The accumulated mass stream is accelerated using electric energy. It is highly important to ventilate the CO_2 / air mass stream in the growth chamber or directly distribute it to the plants because otherwise CO_2 will disperse unevenly because of its higher density compared to air.

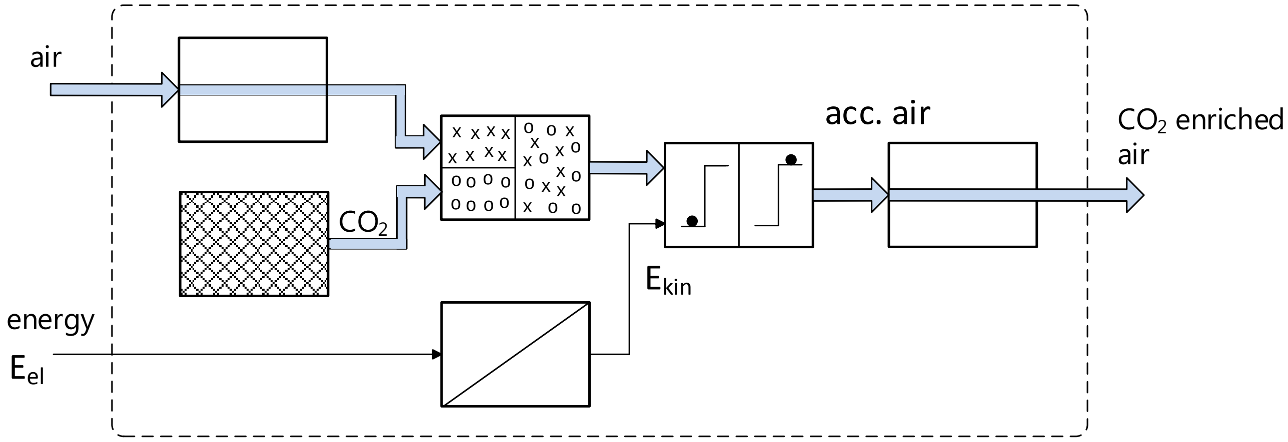
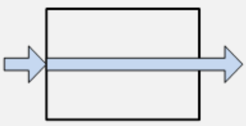
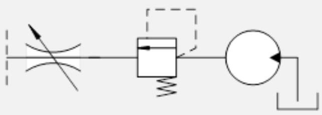
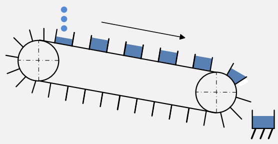
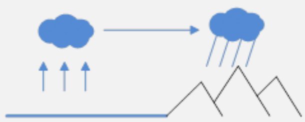
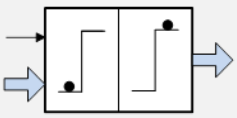
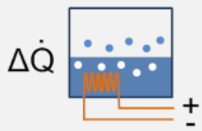
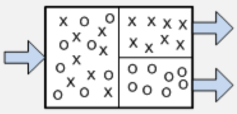
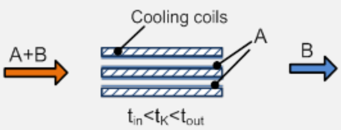
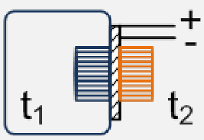


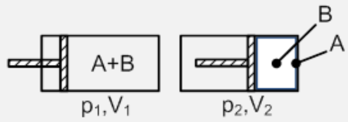
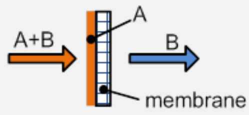
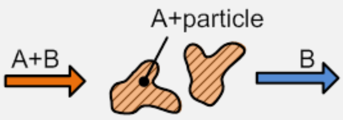
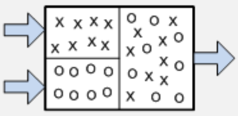
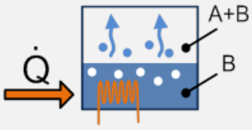
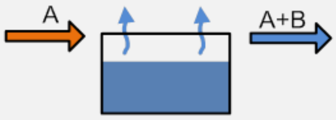
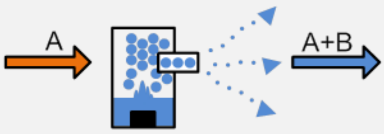
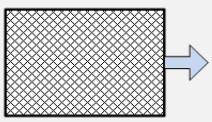
Figure 16: Generally valid function diagram for CO_2 injection

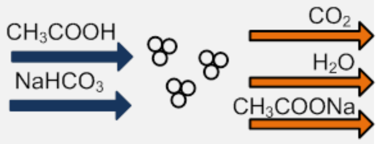
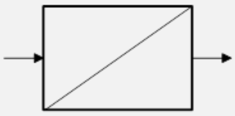
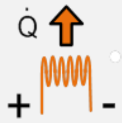
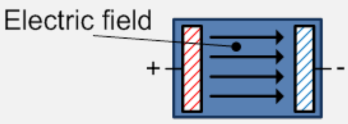
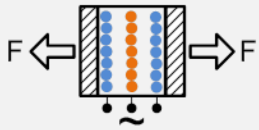
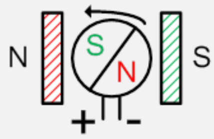
4.3 Working principles table

There are several physical effects that can be used in order to fulfill the tasks stated in the previously developed generally function diagrams. Physical effects are extracted from catalogues (Koller 1998, Koller 1994) and using the analogy method by reverse engineering market available products. Analogies for dehumidifiers are found searching for patents and products to dehumidify swimming pools, to dry moist walls, to dry humid rooms, for grocery production, for greenhouses, for computer/server room cooling, for life support systems and pneumatics. Analogies for humidifiers are found searching for patents and products to humidify rooms, for show effects, grocery production and greenhouses.

Table 3: Selected working principles table for dehumidification, humidification and CO_2 production

Effect	Physical effect	Principal solution	Example
Transfer mass 	Moving medium/ Fixed frame		Piping; Pumps
	Fixed medium / Moving frame		Convoyer belt; Wiper
	Different densities and gravity		Weather
Rise energy level 	Heating		Water boiler
	Accelerating		Fan
Separate material 	Condensation / Temperature difference		Film condensation
	Condensation / Temperature difference		Refrigerator

	Condensation / Partial pressure difference		Piston compressor
	Diffusion		Diffustion through polymer membrane
	Adsorption		Adsorption dehumidifier
	Absorption		Salt, Lithium
	Mass inertia		Cyclone seperator for compressed air
Mix material 	Vaporization		Kettle
	Evaporation		Plant transpiration
	Atomizing		Mister, Ultrasonic humidifier
Isolated CO2 Storage/Production 	Technical gas storage		Gas cylinder
	Combustion, exotherm reaction		Combustion chamber
	Biological reaction		Mycelium, Yeast bacteria

	Chemical reaction		Kipp's apparatus
Convert electric energy 	Resistor		Heater
	Electrostatic field		Electrode Vaporization
	Piezo-effect		Piezo atomizer
	Electro-magnetic fields		Electric motor

4.4 Concept design

4.4.1 Concept design for dehumidifier

The following section gives an overview of a selection of suitable concepts for air dehumidifiers. The concepts are divided into single growth chamber dehumidifier, single air stream dehumidifier and two air stream dehumidifier. The single growth chamber dehumidifiers focus on a solution of a single dehumidifying device for each growth chamber. The single air stream dehumidifiers are centralized devices using a ventilated air stream which connects all growth chambers. The two air stream dehumidifier provides a solution for transferring humidity from one air stream to a second one which is conditioned for optimal dehumidification.

Single growth chamber dehumidifier

The single growth chamber dehumidifiers are directly integrated into the growth chambers. A link between the chambers is not necessary. The main advantages of these systems are the prevention of disease spreading in combination with a single growth chamber humidifier/ CO_2 injection and the modular design. The main disadvantages are the increased number of parts/interfaces and efforts spend for individual control of each growth chamber, leading to higher costs.

Table 4: Pro and contra of single growth chamber dehumidifiers

Pro	Contra
▪ Preventing disease spreading ▪ High flexibility in day / night scheduling, Independent day/night schedule	▪ Increased number of parts ▪ More interfaces/control effort needed

The single growth chamber concepts use the physical effect of condensation (different dew points). To determine the feasibility, the necessary heat transfer coefficient is estimated (Formula 7). The heat transfer coefficient is given by α, the total heat transfer $\dot{Q}$, the cooling surface $A_{surface}$, the temperature of the cooling surface T_w and the temperature of the growth chamber Air T_f.

$$\alpha = \frac{\dot{Q}}{A * (T_w - T_f)} \; [\frac{W}{m^2 K}] \tag{7}$$

A high heat transfer coefficient would require a highly ventilated air and respectively a deranged growth climate. Assuming a constant heat transfer rate of 350 W (for dehumidifying 5,3 l/d in a single growth chamber), a constant temperature of 8 °C at the surface, 25 °C (80% RH) in the growth chamber and a surface area of 0.5 m² the equation solves (Formula 8):

$$\alpha = \frac{350\, W}{0.5\, m^2 * (25\, °K - 8\, °K)} = 41\, \frac{W}{m^2\, K} \tag{8}$$

According to VDI 2055 this value is for a metal-air pairing in the moderately ventilated air range, if the air stream is directed vertical to the surface (see Appendix: Heat transfer coefficient table). The average coefficient of heat transfer for water to air in moderately ventilated air is with $\alpha = \; 25\, \frac{W}{m^2\, K}$ (DIN EN ISO 6946), which is lower than the calculated value. Consequently the condensate might need to be wiped continuously for low air ventilation rate and effective dehumidification.

Concept 1 – Cooling medium / heating coil / wiper condensate dehumidifier

This concept uses a cooling medium, which cools down a metallic surface below the dew temperature of water. Hence, water condensates on the metallic surface. A moving wiper transports the water to the drainage for further use. A moderate air velocity at the surface increases the heat transfer coefficient and thus the condensation rate. Heating coils are shown in this concept to prevent the cooled surface from cooling the growth chamber. Since the light sources in the growth chamber produce heat as well, an additional heating through heating coils might not be necessary.

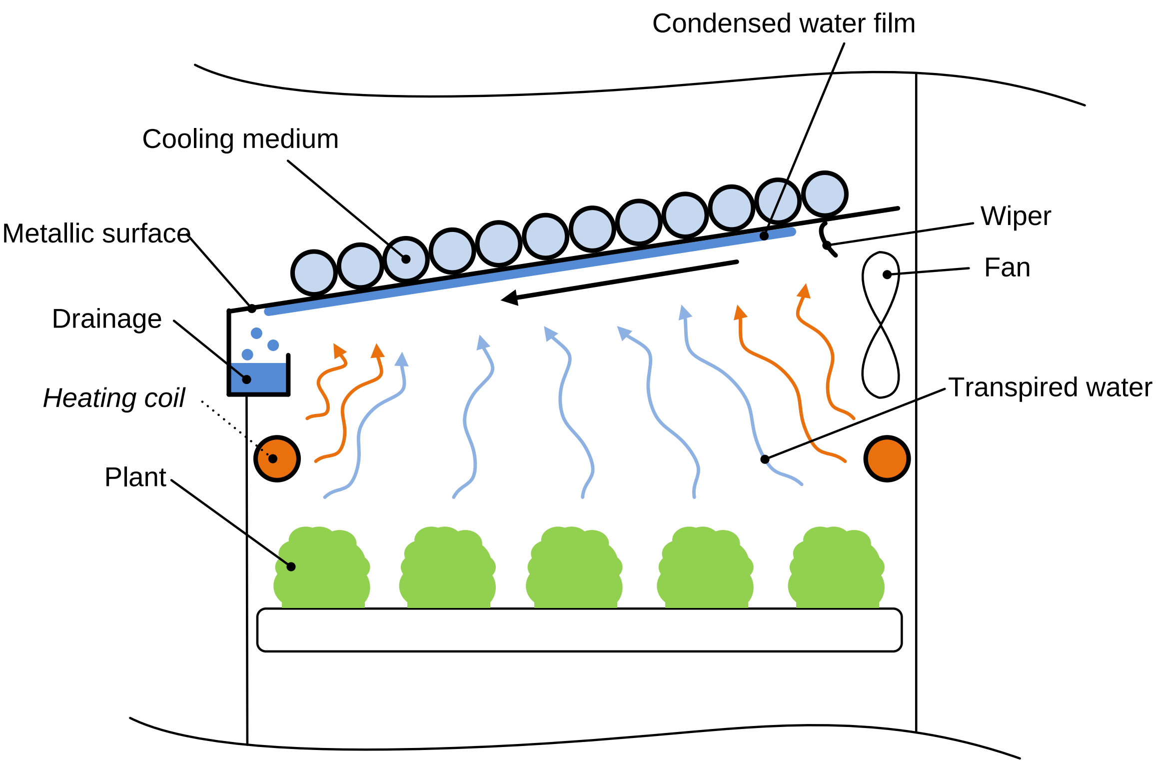


Figure 17: Concept drawing of the cooling medium / heating coil / wiper condensate dehumidifier

Table 5: Pro and contra of the cooling medium / heating coil / wiper condensate dehumidifier

Pro	Contra
▪ Low complexity of components ▪ Low wind speed required ▪ Quiet	▪ More control effort dehumidification individual per tent ▪ More interfaces needed

	▪ Wearing effects at the wiper/surface tribosystem

Concept 2 – Cooling medium / heating coil / conveyer condensate dehumidifier

The conveyer condensate dehumidifier concept shown in

Figure 18 is similar to the wiper system. A conveyer is used instead of a metallic surface. Water condensates on the conveyer and is transported to the drainage. A static wiper is used to wipe off water from the conveyer.

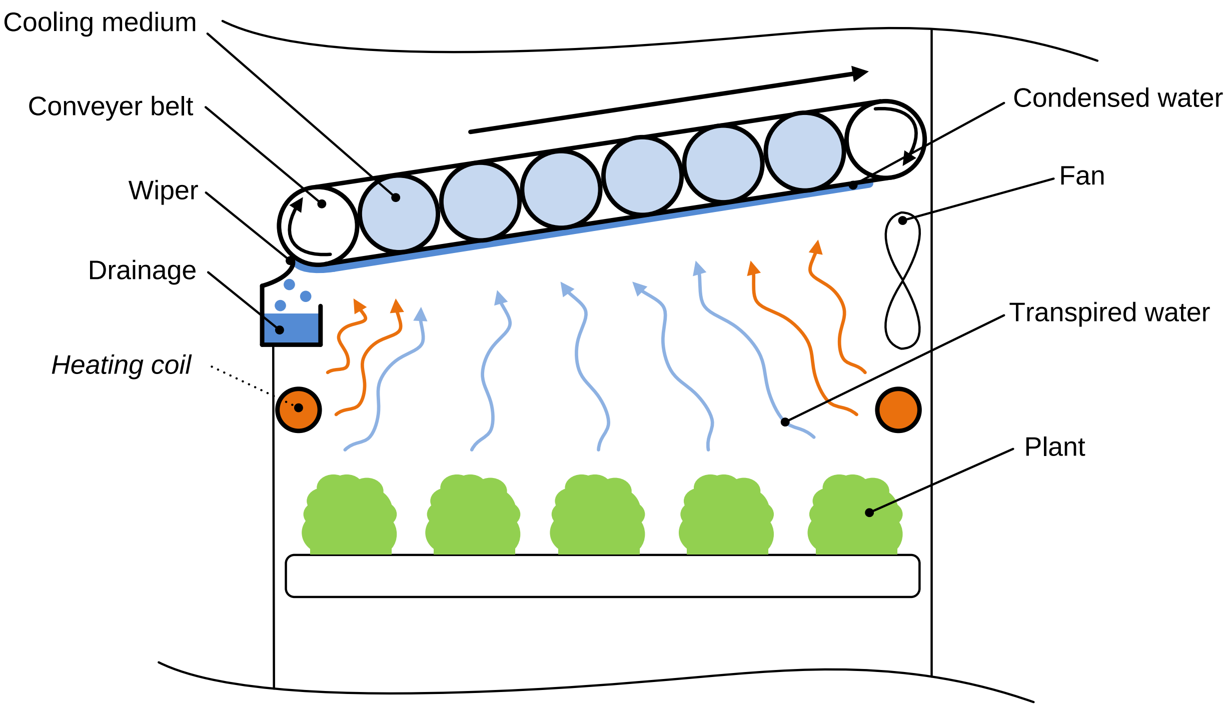


Figure 18: Concept drawing of the cooling medium / heating coil / conveyer condensate dehumidifier

Table 6: Pro and Contra of the cooling medium / heating coil / conveyer condensate dehumidifier

Pro	Contra
▪ Medium complexity of components ▪ Low wind speed required ▪ Easy to maintain ▪ Quiet	▪ More interfaces needed ▪ Wearing effects at the wiper/surface tribosystem ▪ High wind speed required due to low heat transfer between rubber and cooling medium

	▪ More interfaces needed

Concept 3 – Peltier element condensate dehumidifier

Figure 19 shows a concept using peltier elements instead of a cooling coil. For the peltier elements, electrical energy is necessary. A variation of this concept for dehumidifying control boxes is patented under DE 10 2009 008 233 A1. As seen in the aforementioned concepts above, a metallic surface is cooled down below the dew point of water to ensure the effect of condensation. In this concept, no wiper is used. To ensure the desired heat transfer even with a moisten surface, a higher air ventilation or a larger surface area is necessary.

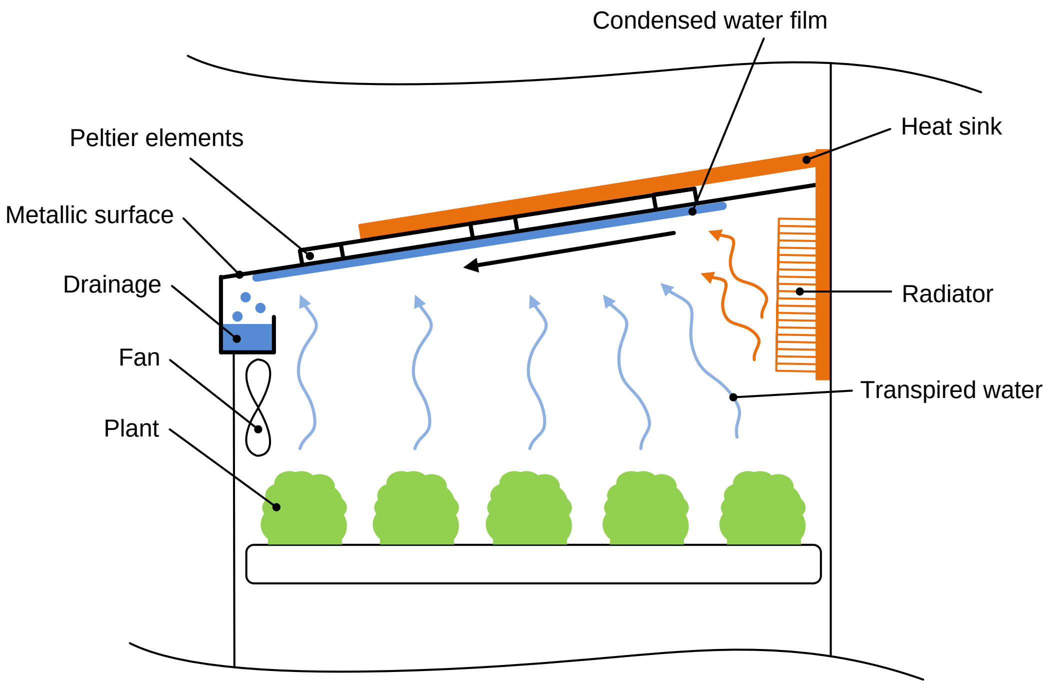


Figure 19: Concept drawing of the peltier element condensate dehumidifier

Table 7: Pro and contra of the peltier element condensate dehumidifier

Pro	Contra
▪ Low complexity of components ▪ Peltier elements are easy to control ▪ No cooling medium required ▪ Quiet	▪ High energy consumption ▪ More interfaces needed ▪ Limited lifespan of the peltier elements ▪ Bigger cooling surface necessary or higher air ventilation required due to wiper free system

	▪ Low efficiency (only 1/10 electric energy to heat energy)

Single air stream dehumidifier

Single air stream dehumidifiers unify all incoming air streams to a single air stream which is dehumidified in a central process. The main advantage of such systems is the cost efficiency of the components through centralizing the system. The main disadvantage is the possibility of interchanging bacteria, viruses and fungi spores between the growth chambers, which might cause crop loss. Especially plants infected with fungi are difficult to separate from healthy plants, while bacteria infected plant can be separated easily (Fladung 2013).

The described concepts use the complete air stream for dehumidification. It is also possible to separate the central air stream into two streams, where one air stream is conducted through the dehumidifier to condition the second air stream for the desired humidity.

Table 8: Pro and contra of single air stream dehumidifiers

Pro	Contra
▪ Cost efficiency due to central dehumidification device	▪ Same climate in all chambers, no independent day/night schedule ▪ Disease spreading between growth chambers ▪ Piping takes space ▪ Increased noise due to fans in the ventilation system

Concept 4 – Cooling medium / heating coil condensate dehumidifier

A classic method for dehumidifying air is the use of cooling coils (Figure 20). This concept is widely used in commercial air conditioning systems. A cooling medium is used to cool down the coil below the dew point to condensate water. The air stream is then conducted to a heating coil to heat the cooled air to the desired temperature. The heating coil can be operated electrically or with a heated fluid. A fan is installed at one point in the air stream for circulation.

Cooling coils are traditionally built of several layers of thin metal sheets and tubing (Figure 21). Common materials used are copper-nickel and copper-aluminum alloys. Usually, air filters and air sterilizers are installed in the air system leading to the coil to prevent pollution.

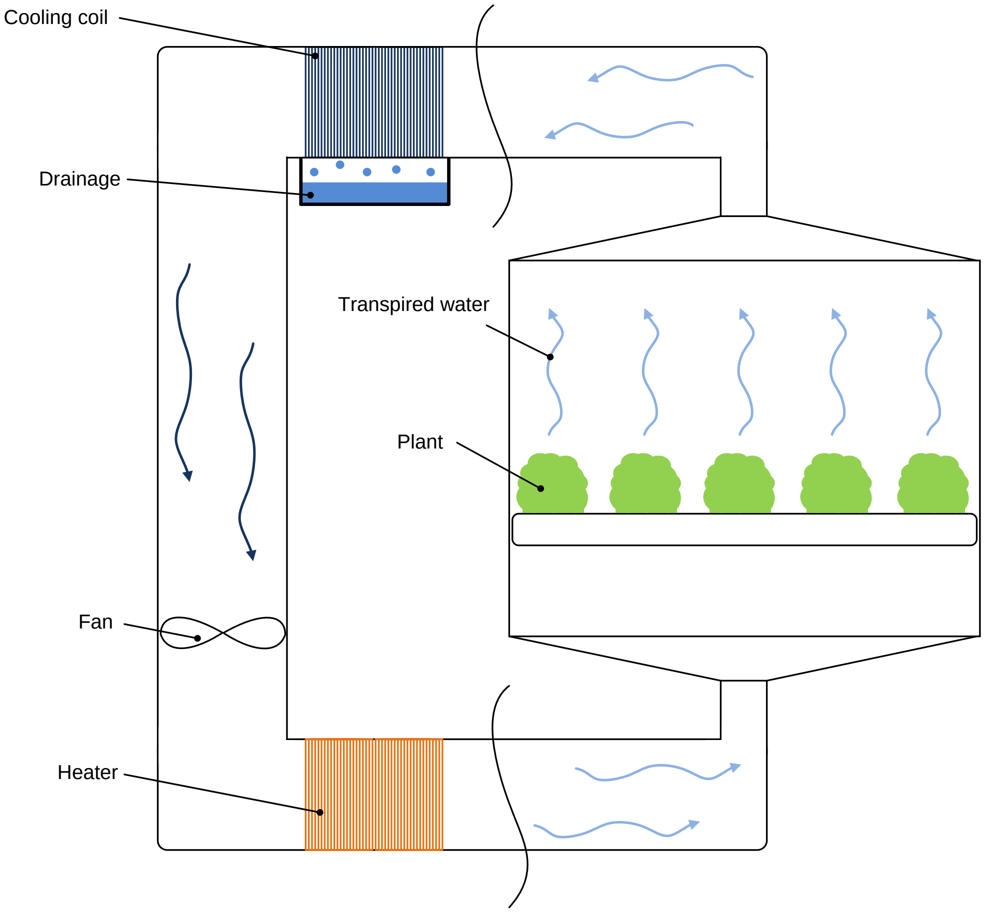


Figure 20: Concept drawing of the cooling medium / heating coil condensate dehumidifier

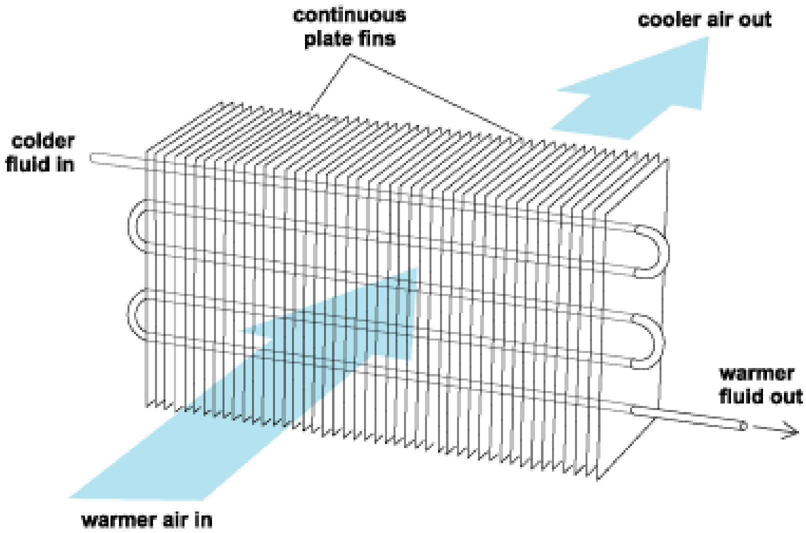


Figure 21: Principle drawing of a cooling coil (Source: ComputerHQ)

Another design of a heat exchanger is currently under development at NASA Glenn Research Centre. As seen in Figure 22 and Figure 23, a porous substrate is used instead of metal sheets to transfer heat applied by the cooling tube. The condensed water is sucked into the substrate by capillary forces. A porous tube inside the substrate is used to conduct the condensed water by applying a pressure difference of around 0,5 bar (7 psi) (Hasan 2006). The advantage of this concept is the reliable operation in microgravity.

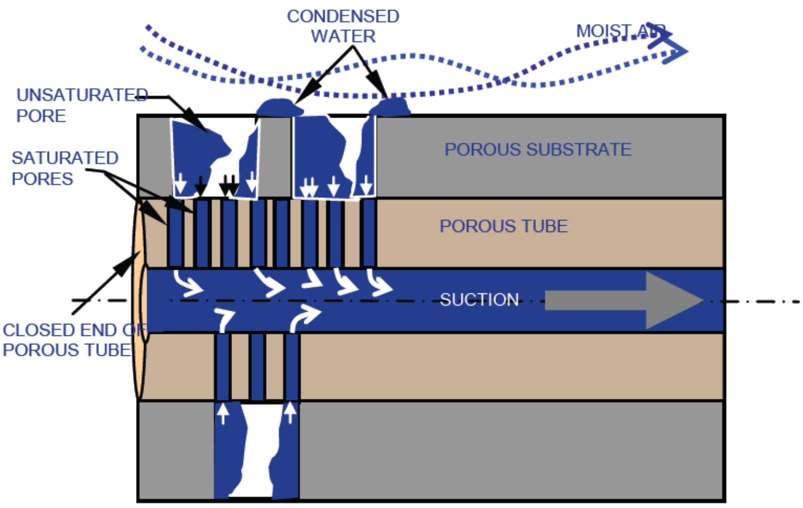


Figure 22: Principle drawing of the porous substrate and condensate removal (Source: Hasan 2006)

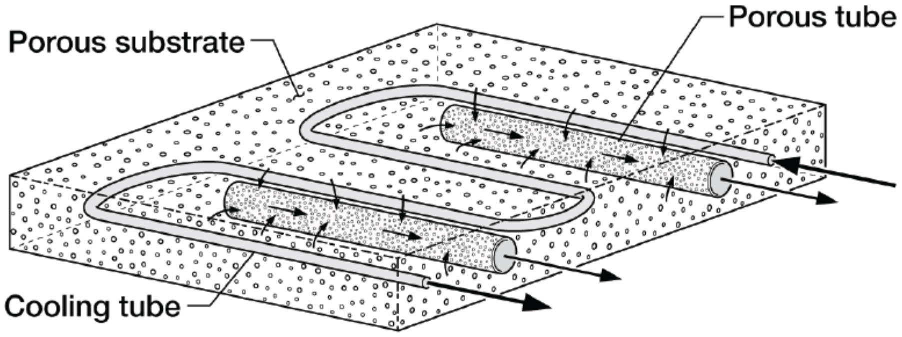


Figure 23: Composite porous media condensing heat exchanger concept (Source: Hasan 2006)

Table 9: Pro and contra of the cooling medium / heating coil condensate dehumidifier

Pro	Contra
▪ Easy to find suppliers for cooling coils ▪ Low number of parts ▪ Easy to control ▪ Quiet ▪ Porous media condensing heat exchange can work under microgravity	▪ Fungus/Bacteria at cooling coils if used without filter ▪ Corrosion might occur at cooling coils ▪ Difficult to maintain ▪ Freezing of coils can reduce the dehumidification rate

Concept 5 – Pressure dehumidifier

Another way of dehumidifying is to compress and cool air. Because of the increasing pressure, the dew point is rising, leading in a condensation at higher temperatures. Figure 24 shows the dew point temperature in correlation to the vapor pressure. The vapor pressure at 100 kPa atmospheric pressure, 60% RH and 30 °C lies at 2.55 kPa. The dew point is at 21 °C. By compressing the air to 1000 kPa, the vapor pressure increases proportional to 255.5 kPa which results in a new dew point of around 61.5 °C.

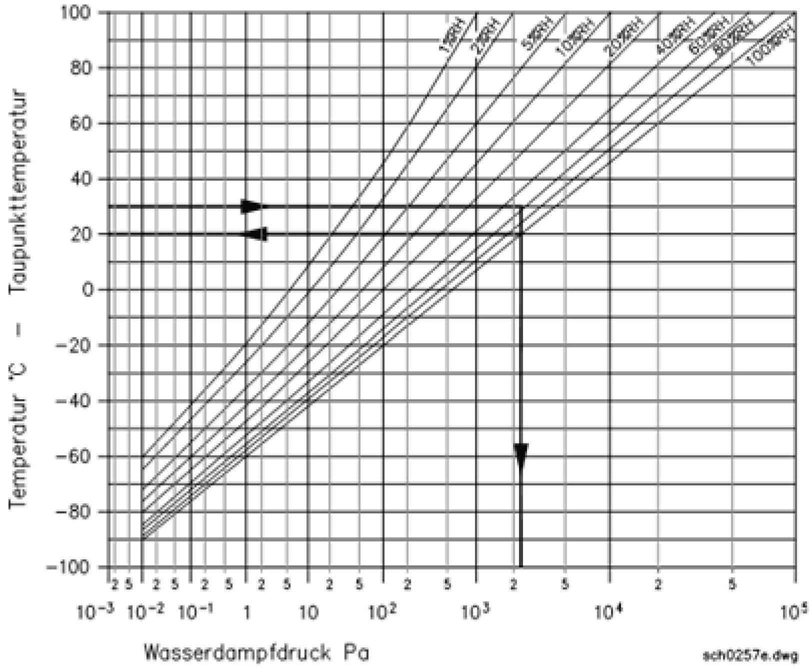


Figure 24: Dew point temperature / pressure diagram (Source: Postberg)

Figure 25 shows a concept drawing of a system using this method. The air mass stream is conducted to a compressor. According to the law of Gay-Lussac the temperature is raised due to the shrinking volume. While the cylinder cools down either actively or passively using ambient temperature, the dew point remains constant at a high level. The water starts condensing while the temperature is decreasing. The condensed water is conducted out of the cylinder. An air valve is opened after the cylinder decompresses the air to ventilate it back to the growth chamber. The air temperature decreases while being decompressed which means that an additional air heater is required. This method is found mainly in pneumatics to prevent corrosion in downstream devices.

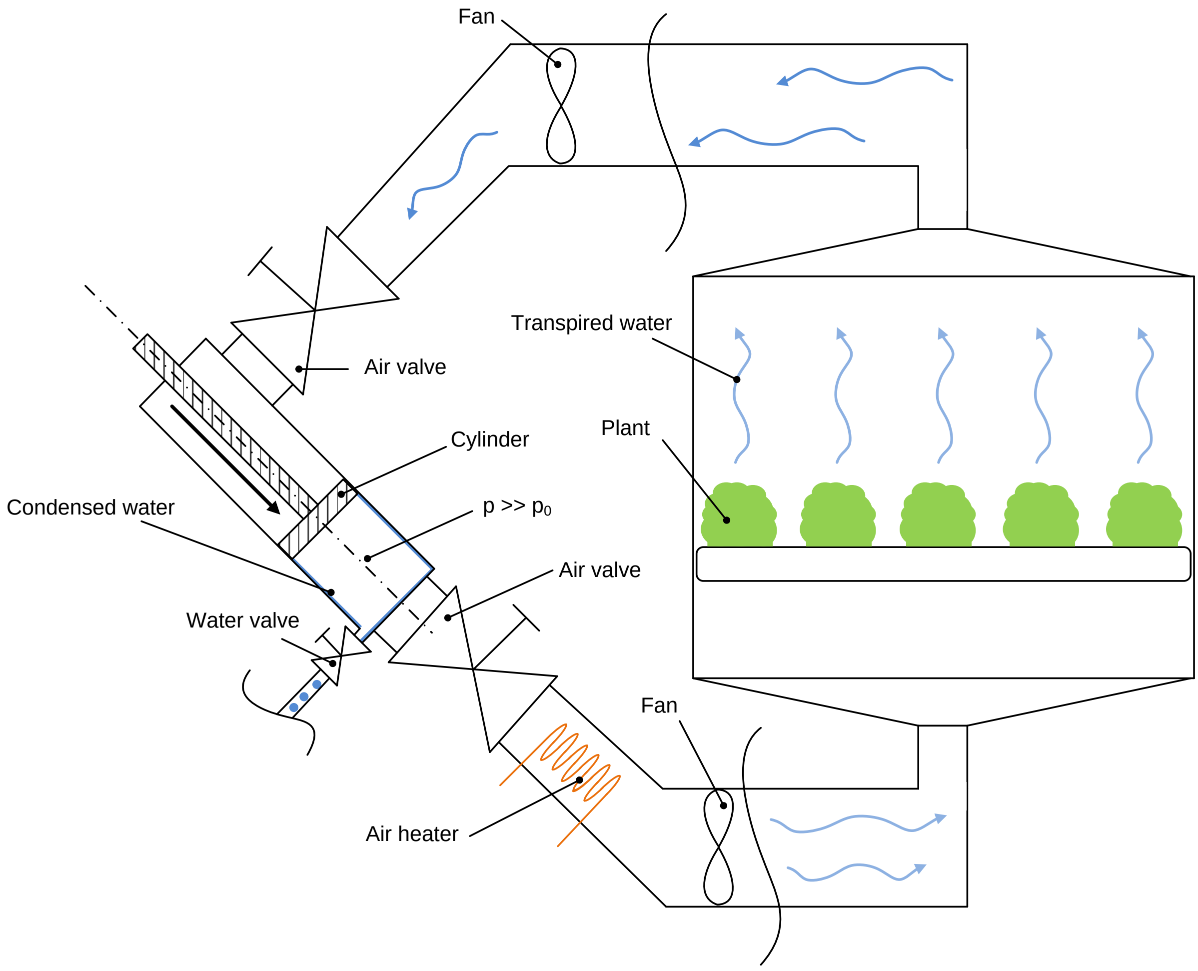


Figure 25: Concept drawing of the pressure dehumidifier

Table 10: Pro and contra of the pressure dehumidifier

Pro	Contra
▪ High condensation rate ▪ Easy to control	▪ Decompressed air can freeze the valves ▪ Difficult to maintain ▪ Many parts needed ▪ High energy consumption ▪ Noise because of compressor ▪ Difficult to control temperature ▪ Difficult to create modular design

Concept 6 – Absorbing dehumidifier

A concept using absorption effect is showed in Figure 26. The wet air stream is conducted either through or across a desiccant. Common desiccant are listed in Table 11.

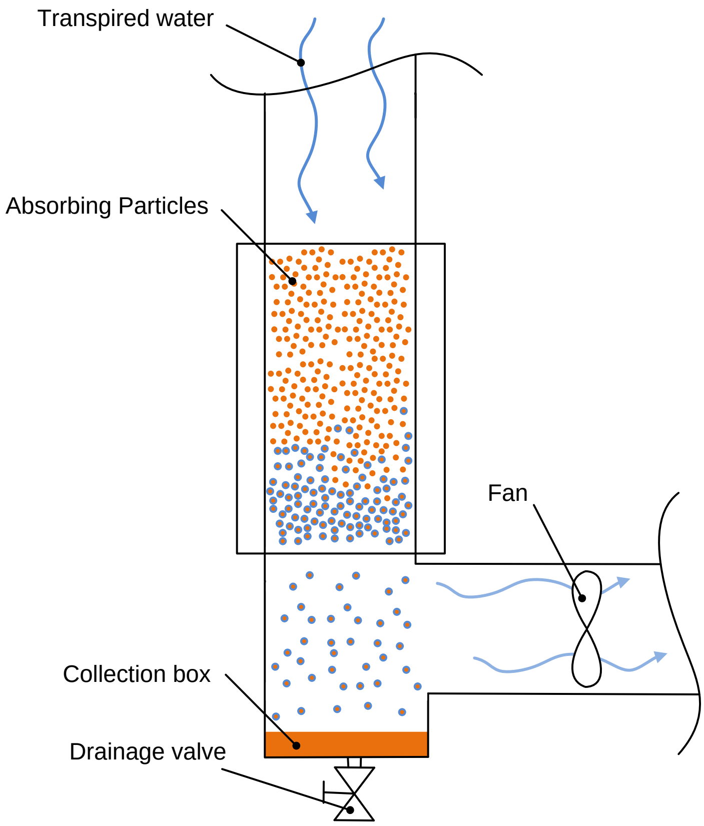


Figure 26: Concept drawing of the absorbing dehumidifier

Table 11: Common desiccants for dehumidification (Bierbaum 2004)

Solid	Liquid	Solvable
▪ Dehydrated chalk ▪ Hyperacid magnesium salt	▪ Lithium chloride ▪ Calcium chloride	▪ Sulfuric acid ▪ Phosphoric acid ▪ Glycerin triethylene glycol

Solvable desiccants become liquid during the absorbing process. Solid and liquid desiccants react with water while keeping their aggregate state. However, the dehumidification rate is highly dependent on the absorbing ability of the desiccant. The ability is changing during time and desiccant saturation which means that a constant regeneration of the desiccant is required (Bierbaum 2004). To prevent additional pollution in desiccants, a filter in the air stream is required.

Table 12: Pro and contra of the absorbing dehumidifier

Pro	Contra
▪ No influence on temperature ▪ Quiet ▪ No external energy needed	▪ Particles need to be regenerated ▪ Low dehumidification rate ▪ Difficult to control ▪ Water and particles need to be separated afterwards ▪ Desiccants highly corrosive ▪ Particles can be transported in the growth chambers ▪ Maximal temperature 30°C (Bierbaum 2004)

Two air stream dehumidifier

Two air stream dehumidifiers consist of an air stream for linking the growth chamber air streams to a central point where the water is exchanged to a secondary air stream which is conditioned for optimal dehumidification. The second air streams needs to be dehumidified afterwards using one of the options mentioned above or by using a cyclone separator. The cyclone separator uses the effect of different inertia of water and air (Figure 27). A humid air stream enters the separator and forces water and heavy dust/dirt particles up to 50 µm to the outer housing. The air stream needs to be saturated for successfully inducing the effect.

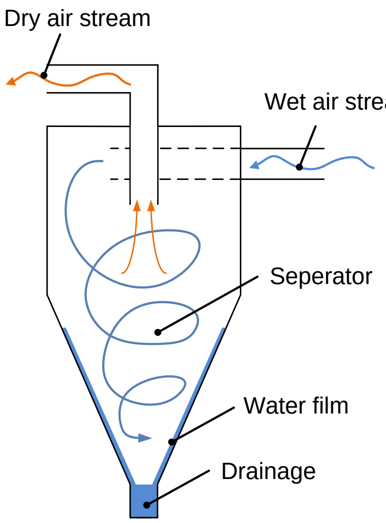


Figure 27: Principle drawing of a cyclone separator

To increase the effectiveness of the cyclone separator, the housing can be cooled. The advantage of this system is the small influence on the attributes of the primary air stream besides the dehumidification. The disadvantages are the increased effort for dehumidifying the secondary air stream and the risk of spreading a disease to all growth chambers.

Table 13: Pro and contra of the two air stream dehumidifiers

Pro	Contra
▪ Small influence on growth chamber temperature ▪ Particle separation if using cyclone separator also filters dust particles	▪ Same climate in all chambers, no independent day/night schedule ▪ Disease spreading between growth chambers ▪ Increased effort for dehumidification ▪ Piping takes space ▪ Increased noise due to fans in the ventilation system

Concept 7 – Adsorbing dehumidifier

A concept for exchange water from the primary air stream to the secondary air stream using the effect of adsorption is shown in Figure 28. Water can be bound to adsorbing particles using attractive forces of molecules. Adsorbing particles have a porous outer surface and a large inner surface to bind large quantities of water. Common adsorbing particles are:

- Activated aluminum oxide (Al_2O_3)
- Silicon dioxide (SiO_2)
- Activated carbon
- Molecular sieve (Na, AlO_2, SiO_2)

The particles are stored in an air-permeable rotating box located in the primary air stream to achieve this effect. By rotating the box, the dehumidification rate can be controlled. To regenerate the particles after absorption, the secondary air stream needs to be either extremely dry or heated up to 120°C – 350°C depending on the adsorbing particles, to overcome the adhesion force. An air filter is necessary to prevent pollution of the adsorbent agent.

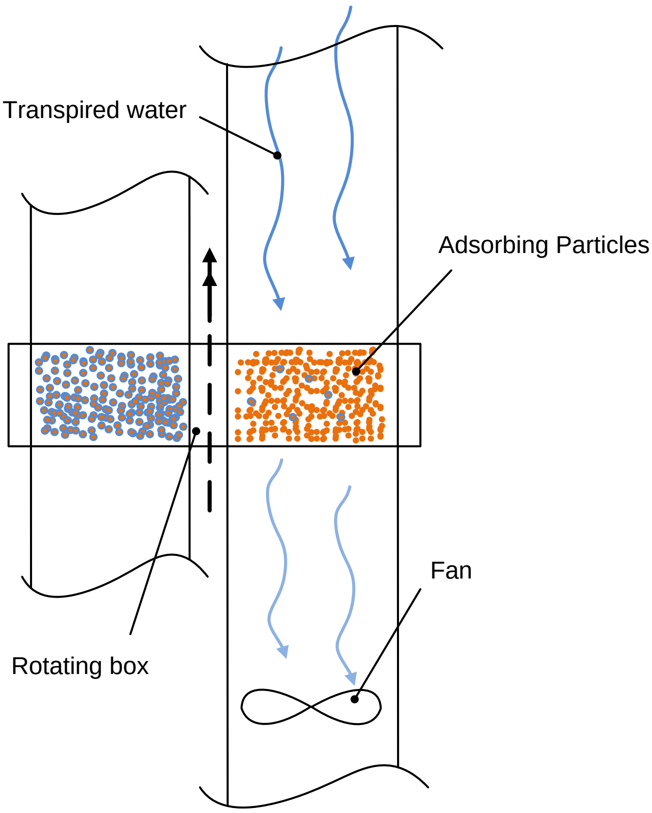


Figure 28: Concept drawing of the adsorbing dehumidifier

Table 14: Pro and contra of the adsorbing dehumidifier

Pro	Contra
▪ No influence on temperature ▪ Low maintenance required ▪ Quiet	▪ Cavities in rotating box ▪ Water and particles need to be separated afterwards ▪ Difficult to control

Concept 8 – Solid-polymer electrolyte dehumidifier

A principle drawing of a polymer electrolyte membrane is seen in Figure 29. Applied to the primary air stream, the porous electrodes attract moisture from the air. Water is absorbed by the membrane and the elements are decomposed by using electric energy. Hydrogen ions are transported through the membrane towards the second air stream, where they are re-leased and form water (Sakuma 2010).

This relatively new technology is mainly used to dehumidify very small volumes like enclosures for electronic circuits to protect the components from moisture.

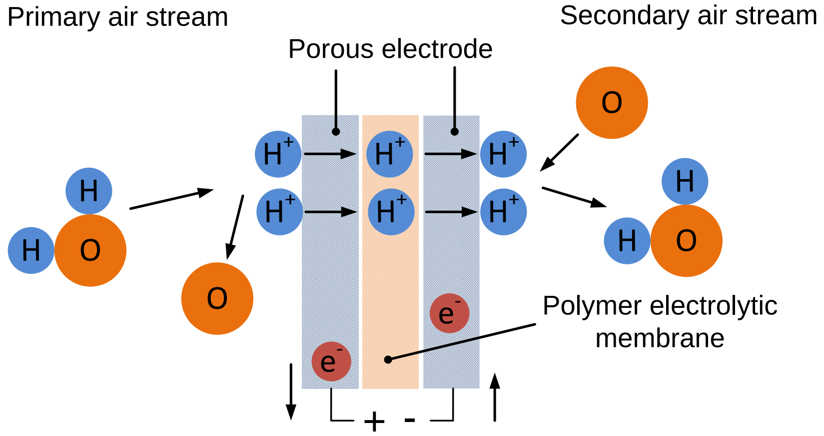


Figure 29: Principle drawing of the polymer-electrolyte-membrane

A concept drawing is seen in Figure 30. The polymer-electrolyte-membrane is used to dry the primary air stream and transferring the moisture to the secondary air stream, which needs to be regenerated afterwards.

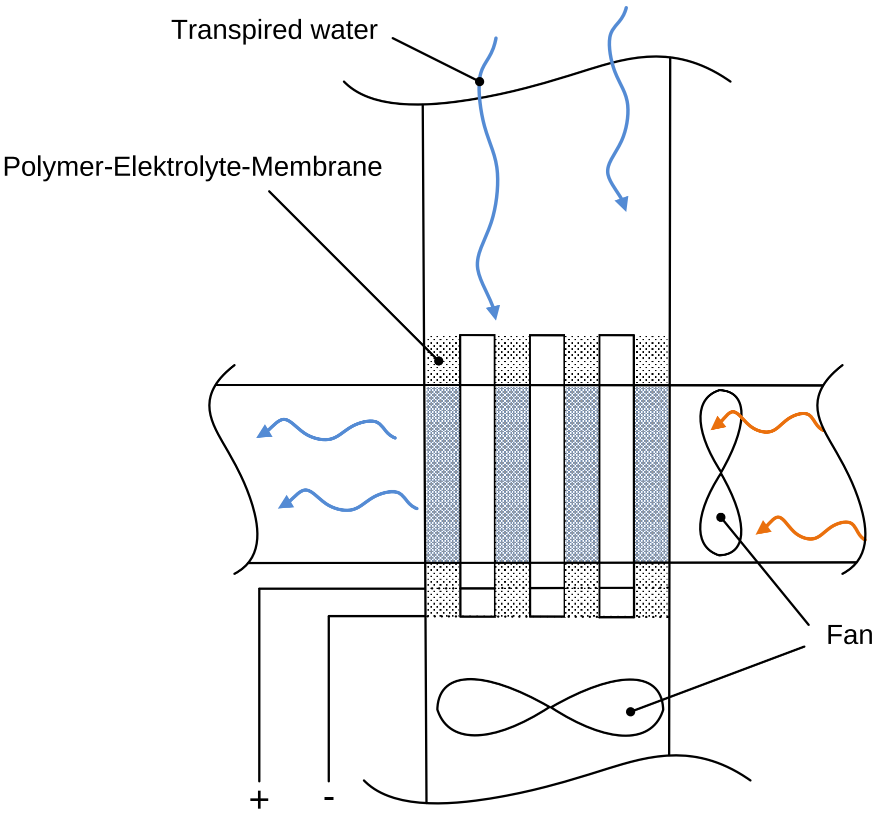


Figure 30: Concept drawing of the solid polymer electrolyte dehumidifier

Table 15: Pro and contra of the solid-polymer electrolyte dehumidifier

Pro	Contra
▪ Easy to control ▪ Low energy consumption ▪ Maintenance-free ▪ Quiet	▪ Currently used dehumidifiers provide Very low dehumidification rate and are only suitable to small volumina

4.4.2 Concept design for Humidifier

Humidifiers are used to distribute water aerosols into the air. Several physical effects can be used to fulfill this task and are explained in the following. Humidifiers are generally smaller in size, if the supply water tank is not taken into account, than the dehumidifiers since the distribution of water aerosols does not necessarily require large surfaces. Therefore, humidifiers can be integrated centralized into the air stream which connects all growth chambers (Figure 31) or decentralized in every growth chamber (Figure 32). Similar to dehumidifiers, a centralized device is more cost effective while the risk of hazardous spreading of diseases is increased.

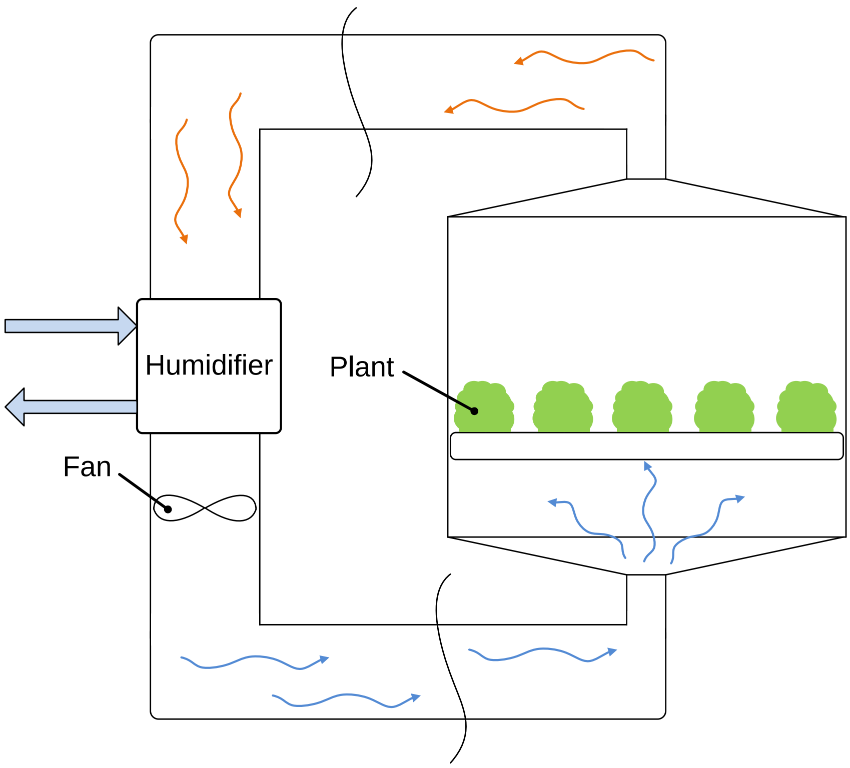


Figure 31: Centralized humidifier inside air stream

Table 16: Pro and contra of a centralized humidifier

Pro	Contra
▪ Low number of parts ▪ Low control effort	▪ Increased risk of disease spreading ▪ Higher effort to create modular design ▪ Increased noise due to fans in the ventilation system

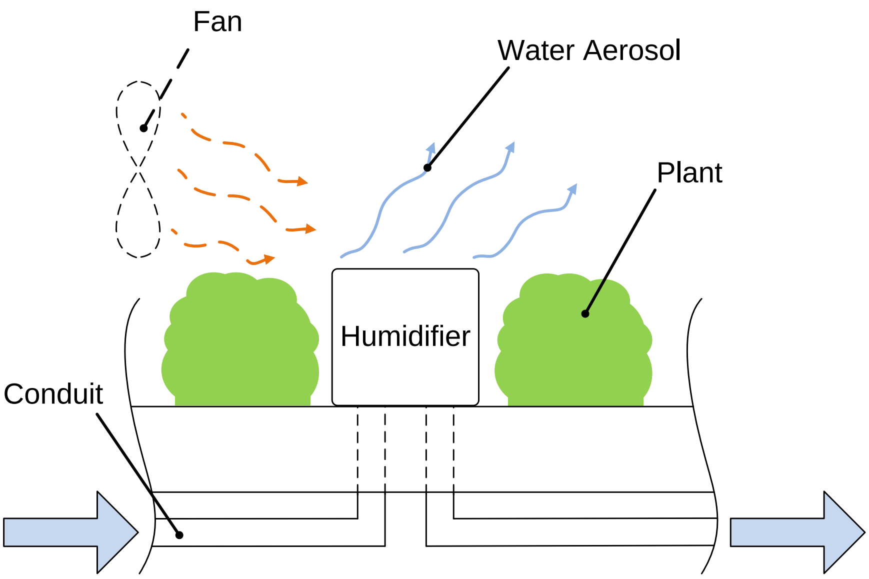


Figure 32: Humidifier inside growth chamber

Table 17: Pro and contra of a decentralized humidifier

Pro	Contra
▪ Preventing disease spreading ▪ Modular design by concept ▪ Individual humidity control per chamber possible	▪ Increased number of parts ▪ More interfaces needed ▪ More control effort needed

Concept 1 – Piezo humidifier

A Piezo dehumidifier is shown in Figure 33. The piezo element transforms electric energy to a mechanic vibration. This vibration creates ultrasound which is transported through the water column on top of the element to the boundary layer. The constant vibration of the water causes cavitation which leads to capillary waves. These capillary waves release very small water aerosols to the air and increase the humidity. The piezo cannot operate without a water column. A filling level meter can be a useful addition to prevent damage of the piezo. For this concept, the piezo is located in a water tank, which is supplied with water from an osmosis machine through tubing and a water valve. For humidification, a defined amount of water enters the tank and the piezo is activated. Excessive water is conducted out of the humidifier by opening the drainage valve. The misted air is released directly to the growth chamber or the air stream.

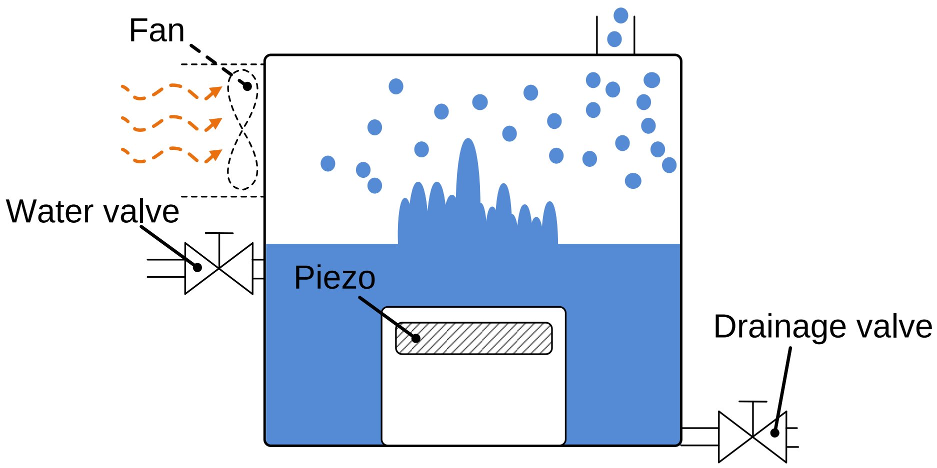


Figure 33: Concept drawing of a piezo humidifier

Table 18: Pro and contra of the piezo humidifier

Pro	Contra
▪ Easy to control ▪ Low power consumption ▪ High humidification rate ▪ Easy to create modular design ▪ No influence on temperature ▪ Small aerosol particles (0.001 - 0.005 mm) ▪ No start up time	▪ "Dry run" can destroy the piezo ▪ Limited lifespan

▪ Cheap	

Concept 2 – Vaporization / heating coil humidifier

The Vaporization humidifier as shown in Figure 34 uses a heating coil to heat water to the boiling point. The amount of water inside the heater is controlled by a valve and a flow meter. By controlling the coil temperature and hence the amount of heat energy which is used to boil the water, the humidification rate is controlled. The humidification process stops automatically once the water is vaporized completely. A drainage valve is not necessary.

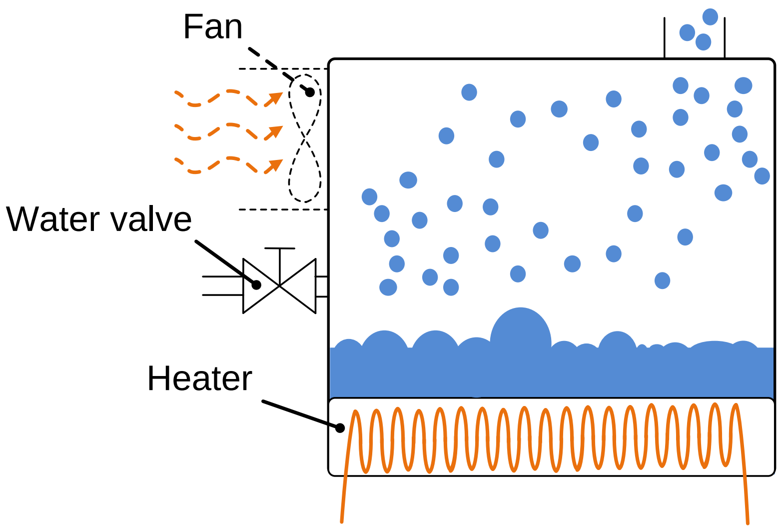


Figure 34: Concept drawing of a vaporization humidifier

Table 19: Pro and contra of the vaporization humidifier

Pro	Contra
▪ Robust ▪ Heating destroys bacteria and fungi ▪ Cheap	▪ High influence on temperature (heating) ▪ Difficult to control (Time delay)

Concept 3 – Vaporization / electrode humidifier

The Vaporization humidifier as shown in Figure 35 uses electrodes instead of heating coils to vaporize water. Heat energy is converted from electric energy by the resistance of water. This solution is common in large air conditions.

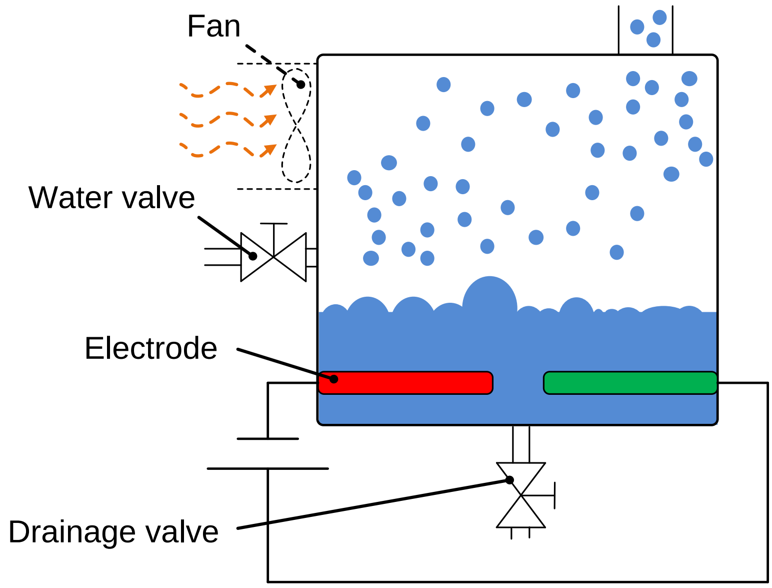


Figure 35: Concept drawing of an electrode vaporization humidifier

Table 20: Pro and contra of the electrode vaporization humidifier

Pro	Contra
▪ Easy to control ▪ Releases large amounts of water in short time ▪ Boiling destroys bacteria and fungi	▪ High influence on temperature (heating) ▪ Difficult to control (Time delay)

Concept 4 – Atomizing humidifier

The Atomizing humidifier deploys water through mister on a sponge (Figure 36). The amount of water is controlled by a water valve and flow meter. Aerosols are directly transferred in the air stream and the remaining water is collected by the sponge and evaporated afterwards. This solution can release large amounts of water in relatively short time.

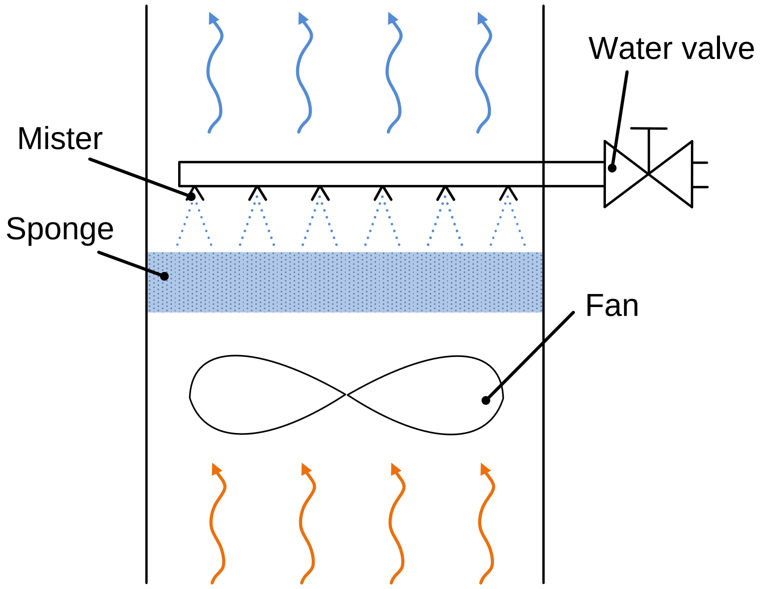


Figure 36: Concept drawing of an atomizing humidifier

Table 21: Pro and contra of an atomizing humidifier

Pro	Contra
▪ Easy to control ▪ Releases large amounts of water in short time	▪ Wearing effects at the mister (growth chamber handbook maintenance) ▪ Risk of fungus/bacteria growth in the sponge ▪ Influence on temperature (cooling) ▪ Difficult ot maintain

Concept 5 – Evaporation / adsorbing humidifier

A concept drawing of an Evaporation humidifier is seen in Figure 37. Adsorbing particles are used, similar to the Adsorbing dehumidifier concept. The box is rotated through the osmosis tank and the air stream afterwards. Because of the very short retention period in the osmosis tank, the water only moistens the outer surface of the adsorbing particles. The humidity rate is defined by the rotation speed of the box. The concept is more feasible if used in a centralized air stream rather than in a single growth chamber.

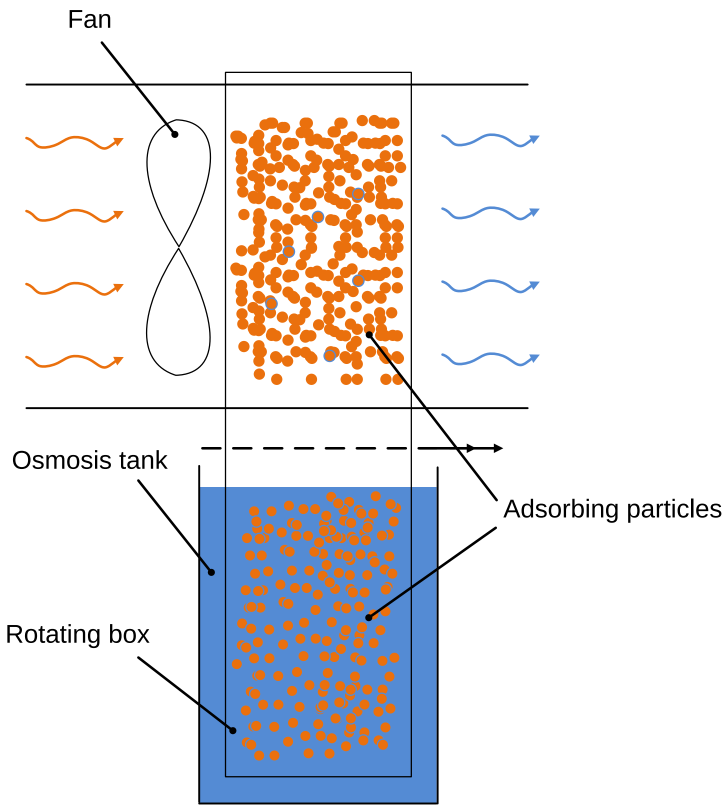


Figure 37: Concept drawing of an evaporation dehumidifier

Table 22: Pro and contra of an evaporation dehumidifier

Pro	Contra
▪ Humidification rate depending on the rotation speed ▪ Low energy consumption ▪ No Aerosols	▪ Difficult to control because of high dependency on the parameters of the air mass stream ▪ Difficult to integrate in single growth chamber

▪ Low influence on air temperature (cooling)	▪ Influence on air stream temperature

4.4.3 Concept design for CO_2 injection

CO_2 can be injected in the plant growth chamber centralized or decentralized similar to the humidifiers. A centralized device injects the CO_2 into the air stream which connects all growth chambers. A decentralized device injects the CO_2 into each growth chamber. A decentralized device does not need an additional fan, since the natural convection in the growth chamber prevents the CO_2 from accumulating at the bottom (Täschner 2009). However, a CO_2 sensor needs to be deployed in each growth chamber to determine the exact level of each time. Four general concepts for producing CO_2 are identified.

Concept 1 - Technical gas deployment

An electromechanical vale is connected to technical gas storage (Figure 38) to inject CO_2 into the air. The CO_2 can be stored either liquid or gaseous. One kilogram of CO_2 equals 0.849 l liquid CO_2 (-56.6 °C and 5.2 bar) and 0,544 m³ gaseous CO_2 (15 °C and 1 bar) (Appendix: CO_2 Datasheet). Hence, a gaseous storage is not feasible compared to the liquid storage because of the additional space needed.

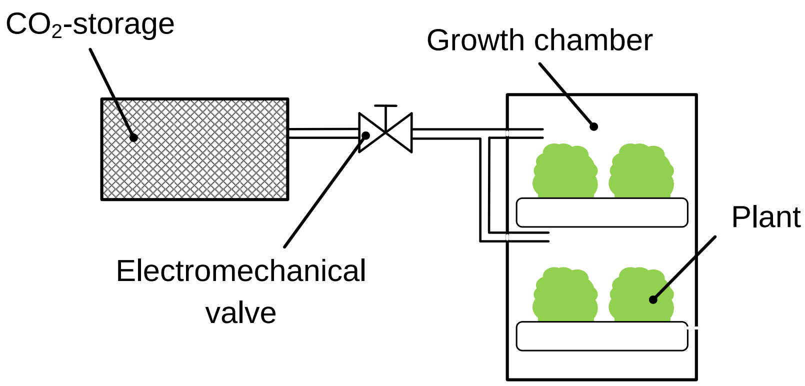


Figure 38: Concept drawing of a technical gas deployment

Table 23: Pro and contra of a technical gas deployment

Pro	Contra
▪ Easy to control ▪ Simple interfaces	▪ Expensive ▪ Large amount of space needed ▪ Not reproducing

Concept 2 - Combustion exhauster

CO_2 can be produced through combustion of alkanes. Methane and propane or mixed natural gas is widely used as fuel. In combination with Oxygen and inertial energy, CO_2 and water is produced. The chemical reaction for propane combustion is given:

$$C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$$

The combustion should take place with high level of oxygen to prevent pollution with unwanted waste products. Around 2 kg CO_2 can be extracted from 1 m^3 of natural gas. For example, 1 kg propane produces 2.96 kg CO_2 (Appendix / Täschner 2009). A concept drawing can be seen in Figure 39.

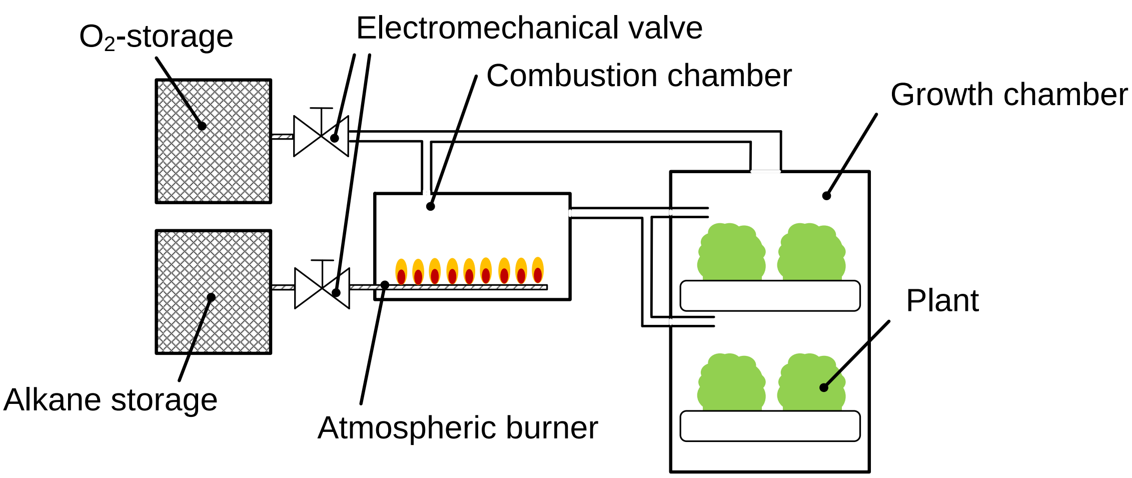


Figure 39: Concept drawing CO_2 source using a combustion chamber

Table 24: Pro and contra of the combustion chamber

Pro	Contra
▪ Cheap production of CO_2 ▪ Easy production in remote locations	▪ Possible pollution with unwanted exhaust ▪ Heating fuel necessary ▪ Produce of heat energy and water ▪ Safety issues because of fire

	▪ Additional installation effort ▪ Not reproducing

Concept 3 - Biochemical reactor

A biochemical reactor produces CO_2 through cell respiration which is a metabolism to create energy in all living beings. The oxidation of sugar is the most common metabolism and therefore explained exemplary. Sugar is oxidized to CO_2, water and energy. The free enthalpy of this reaction is negative, which means that the reaction runs exothermal and thus no additional energy is needed.

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

The reverse of the same chemical equation equals photosynthesis. In a biochemical reactor, several bacteria such as yeast or the cells of mycelium can be used to produce CO_2.

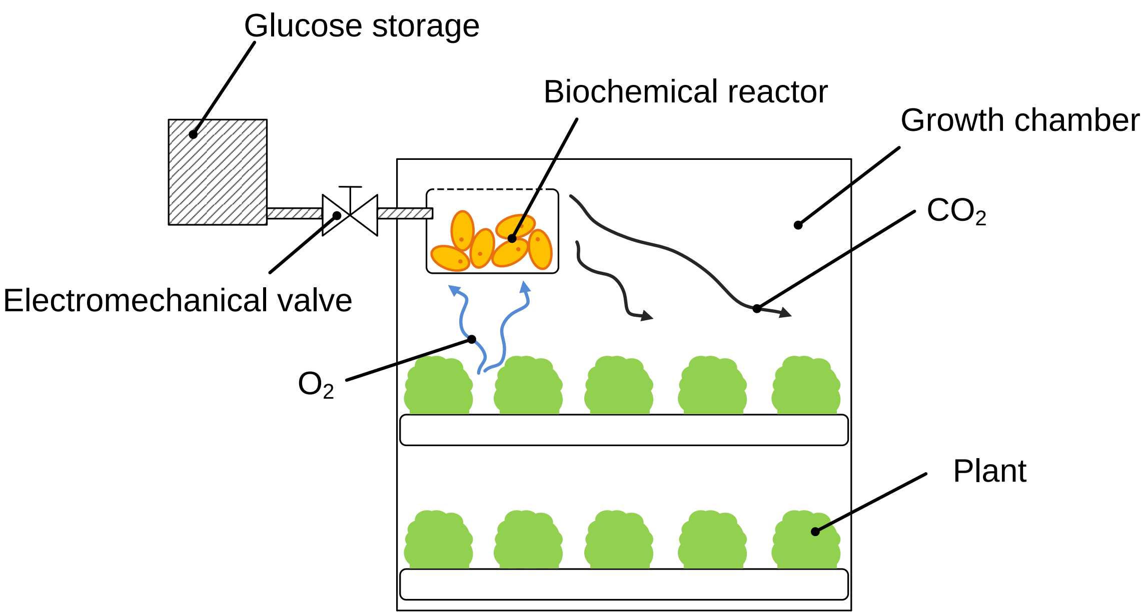


Figure 40: Concept drawing of a CO_2 source featuring a biochemical reactor

Table 25: Pro and contra of a CO_2 source featuring a biochemical reactor

Pro	Contra
▪ Concurrent production of CO_2 ▪ Reproducing	▪ Difficult to control

	▪ Needs Oxygen and additional chemicals (i.e. sugar) ▪ Stopping the production leads to cell death

Concept 4 - Chemical reactor

CO_2 can be produced by using a chemical reactor (Figure 41). As an example, acetic acid and sodium bicarbonate react to CO_2, water and sodium acetate. (Langhans 1997)

$$NaHCO_3 + CH_3COOH \rightarrow CO_2 + \ H_2O + CH_3COONa$$

Acetic acid and sodium bicarbonate are common and cheap chemicals. Acetic acid can be produced through various chemical processes, or through a biochemical reaction of the bacteria Acetobactar or through the oxidative fermentation of alcohols ($C_2H_5OH + O_2$ -> $CH_3COOH + H_2O$) or sugar ($C_6H_{12}O_6 = 3\ CH_3COOH$). Sodium bicarbonate can be produced through distribution of CO_2 into sodium hydroxide ($CO_2 + 2\ NaOH$ -> $Na_2CO_3 + H_2O$ and $Na_2CO_3 + CO_2 + H_2O$ -> $2\ NaHCO_3$). The necessary sodium hydroxide can be produced through electrolysis of sodium chloride and water ($2\ NaCl + 2\ H_2O$ -> $Cl_2 + H_2 + 2\ NaOH$). The side product of the chemical reactor, sodium acetate is used for preservation of food, because of its acidity regulation properties.

While acetic acid is liquid, sodium bicarbonate is solid under atmosphere pressure and 25 °C. Water and sodium acetate form a solution and CO_2 gasses out. The amount of chemicals needed for producing one kilogram of CO_2 is exemplary listed in Table 26.

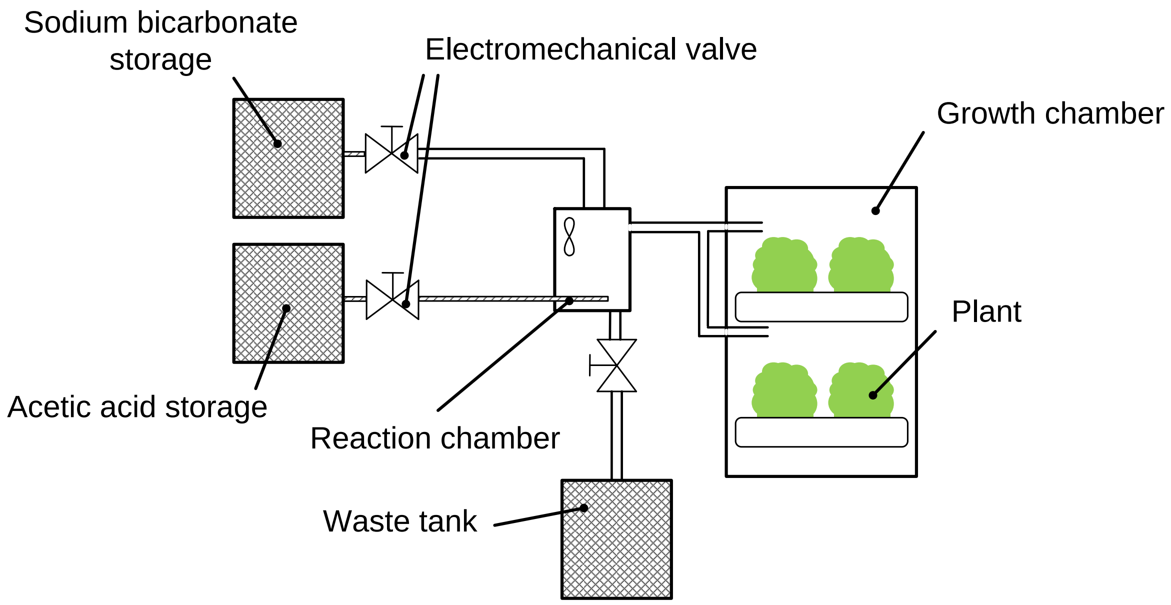


Figure 41: Concept drawing of a carbon source featuring a chemical reactor

Table 26: Chemicals needed for producing one kilogram of CO_2

	Mass (m)	Molar mass (M)	Amount of substance (n)
CO_2	1 kg	44.01 g/Mol	22.722 Mol
H_2O	0.409 kg	18.015 g/Mol	22.722 Mol
CH_3COONa	1.863 kg	82.0343 g/Mol	22.722 Mol
$NaHCO_2$	1.908 kg	84.007 g/Mol	22.722 Mol
CH_2COOH	1.364 kg	60.05 g/Mol	22.722 Mol

Table 27: Pro and contra of a CO_2 source featuring a chemical reactor

Pro	Contra
▪ Concurrent production of CO_2	▪ Difficult to control ▪ Needs additional chemicals ▪ Production of additional chemicals

4.4.4 Measuring humidity

For measuring the amount of water in a gaseous fluid two groups of sensors exist. The first group measures the absolute humidity. The units used for absolute humidity are parts per million (PPM) and Dew/Frost point (D/F PT). While widely spread in many industrial fields, for example for moisture tracing, absolute humidity measurement is generally more difficult to achieve and of minor importance for environmental control. For the application of measuring and controlling humidity in a greenhouse, the common solution is the use of relative humidity sensors (RH). These sensors measure the amount of water in gas in relation to the amount of water in saturated gas at the same temperature (Chen 2005). Hence, relative humidity is temperature dependent and most relative humidity sensors output the dry bulb temperature as well. Various measurement principles can be used to determine relative and absolute humidity:

Gravimetric, elongation, volumetric, psychrometric, hygoscopic (sorption), electrolyte resistance, electrolytic, radiation refraction (microwave and radio), radiation absorption or attenuation (infrared, ultraviolet, microwave, alpha), radiation scattering (neutron), nuclear magnetic resonance, color metric, piezoelectric, electrical capacitance, thermal (heat capacity), thermal conductivity, paper hygrometry (sorption), diffusion, combustion, electrolysis, heat of absorption, piezoelectric sorption, sonic hygrometry, surface acoustic wave, crystal oscillatiograph dew point, thermal dew point (Langhans 1997)

However, common commercial available sensors for absolute humidity measurement use solid moisture and mirror-chilled hygrometers, even though their results can be converted to relative humidity with a simultaneous, additional dry bulb temperature measurement.

The mirror-chilled hygrometers consist of a temperature controlled mirror which reflects light of a light emitting source. The reflection is captured by a light sensor. The mirror is cooled down to the point where water starts condensing at the mirror surface, which stops the light reflection. The temperature of the mirror reaches the dew point of water at this point which is directly related to the amount of water in the air. This method is the most precise measurement of humidity and the most expensive one. Maintenance needs to be done on the mirror, which needs to be cleaned in certain intervals (Chen 2005).

Relative humidity sensors are capacitive, resistive, thermal conductive, gravimetric or psychometric. Capacity based relative humidity sensors consist of water adsorbing materials, which change the dielectric coefficient due to the amount of water. Common sensing materials are ceramics like Al_2O_3, SiO_2, TiO_2, and polymerics. α-Al_2O_3 gives the best results. (Chen 2005) Capacity based relative humidity sensors are widely spread because of the cheap sensor element, high precision, long-term stability, maintenance free use and fast response time.

Resistive based materials also use the adsorbing effect of a hygroscopic medium such as conductive polymer, salt, or treated substrate. Operated under alternating current, these sensors change their impedance due to the level of adsorbed water. Advantages of these sensors are the low cost, small size, interchangeability and long term stability (depending on the material). Disadvantages are the tendency to shift values if water condenses on the sensor due to water-soluble coating, high temperature dependencies if installed in an area with large temperature fluctuations and slow response time (Roveti 2001).

Psychometric sensors compare the temperature of a wet bulb thermometer with the temperature of a dry bulb thermometer in the same surrounding medium. Using a psychometric chart, the relative humidity can be calculated. The accuracy and long term stability of this measurement is high and is highly dependent on the quality of the thermometers. However, it is necessary to keep moisture on the wet bulb thermometer constantly.

Gravimetric humidity sensors measure the weight of the same volume of a dry gas compared to a wet gas to determine the amount of water in the air. This method is mainly used for calibrating sensors.

Another method for analogue measurement of humidity is the use of hair tension hygrometers. The length of a human or synthetic hair is dependent on the amount of absorbed water. Advantage of this technology is its simplicity and the almost temperature independency. Disadvantages are the high maintenance intervals and slow response time.

4.4.5 Measuring temperature

Various solutions for measuring temperature exist and a focus is laid on two widely known measurement principles. A simple method is the measurement of resistance of metal, which is temperature dependent. Platinum shows a high linearity between temperature and resistance and is commonly used. Another method is the measurement of a current through the thermoelectric effect. The sensors that use this technology are widely known as thermocouples.

4.4.6 Measuring CO_2 concentration

Many methods exist for measuring the CO_2 concentration in a gaseous medium. The most common ones are the non-dispersive (NDIR) infrared gas, photo acoustic, electrical conductivity and the photochemical gas analysis.

Photochemical sensors are based on the principle of comparative colorimetry. A chemical gas, which is usually contained in a gas tube, changes its color depending on the concentration of CO_2 in the sample gas. This method is mainly used for spot detection of CO_2 rather than for continuous measurement. Also the precision is limited (Langhans 1997).

Conductive sensors measure the electrical conductivity of dissolved CO_2 in distilled water. The air stream is conducted partially through deionized water in a conductivity cell and the resistance is measured electrically. The resistance increases as the amount of dissolved CO_2 increases. The water is deionized for a continuous measurement. Advantages of the system are the cheap price and the continuous measurement. Disadvantages are the low precision, the necessary routine maintenance and calibration. (Langhans 1997)

Photo acoustic sensors use a flashing light beam at the absorption wavelength of CO_2 which forces the molecules to vibrate, inducing sound. Small microphones in the chamber recognize the sound and a microprocessor calculates the concentration. However, this technology is not sensitive to dirt or dust, but can be affected by light source aging, which reduces the long term stability of the values (drifting). To minimize the effect of light source aging, sensors with stable characteristics and correction algorithms should be used. For a precise measurement, the environment should be vibration free and pressure constant. Additional pressure sensors for correction are available in more expensive products (Schell 2001).

Non-dispersive infrared sensors (NDIR) are the most common option for measuring CO_2 concentration. An infrared light source is placed in line with a selective optical filter and a light detector, which is adjusted to the absorbing wavelength of CO_2 molecules. By measuring the light absorption, the concentration of CO_2 can be determined (Langhans 1997). Due to the fact that many gas atoms absorb infrared light, especially gaseous water which has a similar absorption frequency, a compensational measurement is necessary. Advantages of this sensor are the high short term repeatability and high accuracy. The disadvantage is the signal drift because caused by the aging of the light source similar to the photo acoustic sensors and particle buildup inside the sensor, which can be prevented by using a gas permeable membrane. Generally the signal drift is relatively small in modern NDIR sensors and measurement accuracy of below 50 ppm can be achieved (Schell 2001).

4.4.7 Controlling the process

The control algorithms for controlling the humidity and CO_2 concentration generally run on a digital control platform such as:

- Matlab
- PLC (Programmable Logic Controller)
- LabVIEW
- Embedded microcontroller

Therefore, no analogue controlling is necessary besides the automatic closing of the CO_2 injection valve and if necessary due to safety issues the dehumidification and humidification devices in case of power loss.

The controller concept will be highly dependent on the chosen concept and desired accuracy. Hence it will be implemented in a rapid control prototyping cycle after the hardware setup.

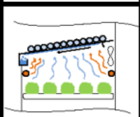
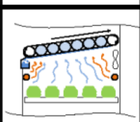
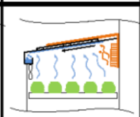
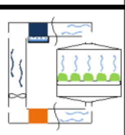
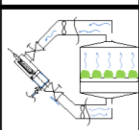
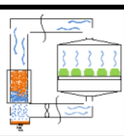
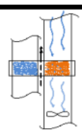
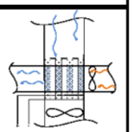
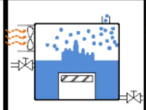
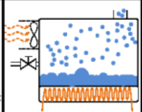
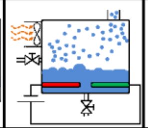
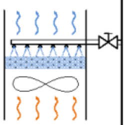
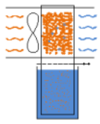
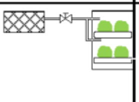
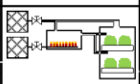
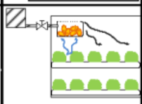
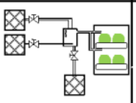
5 System integration

In this chapter, the solutions considered in the conceptual design phase are summarized in a morphological box. The sub functions are taken into account and are going to be evaluated using common engineering evaluation methods to obtain the best overall concept.

5.1 Morphological box

The morphological box (Table 28) gives a summary of all possible solutions for each sub function (laid out in chapter 4).

Table 28: Morphological box

Sub function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8
Concepts for Dehumidifier								
Concepts for Humidifier								
Concept for CO_2 Injection	 Technical storage	 Combustion chamber	 Biochemical reaction	 Chemical reaction				
Measuring Air Humidity (Measurement principle)	Mirror-chilled hygrometer	Capacity	Resistive	Gravimetric	Psychometric	Hair hygrometer (Absorption)		
Measuring CO_2 concentration (Measurement principle)	Photo-mechanical (Colorimetry)	Conductive	Photo acoustic	Non-dispersive-infrared				
Feedback Control system	Matlab	PLC	LabView	Embedded Micro-controller				

5.2 Evaluation

The evaluation of the sub functions is done using common engineering evaluation methods such as the utility analysis. A focus is laid on the dehumidifier and humidifier concepts as they are identified as the most complex and costly components of the system. The other sub functions are evaluated using the direct comparison method focusing on low costs and high compatibility.

5.2.1 Evaluation of dehumidifier concepts

The dehumidifier concepts are evaluated using the utility analysis. The evaluation criteria are derived from the requirements list and extended in an assessment criteria meeting (Zabel 31.10.2013). The sorting and weighting of the criteria is done in close agreement with the project supervisors (Zabel 06.11.2013). The synthesized objectives tree can be seen in Figure 42. The results of the evaluation are displayed in Table 29. The maximum overall rating for a concept is four, while the lowest one is zero. One concept got a zero rating in an assessment criterion and hence rated zero in the overall rating. The detailed evaluation including a description of the assessment criteria can be found in the digital appendix.

Table 29: Results of the utility analysis for the dehumidifier concepts

Concept	Economic efficiency (max. 1.2)	Technical functionality (max. 2.8)	Overall rating (max. 4)
Concept 1 (Wiper cooling system in growth chamber)	0.69	2.268	2.958
Concept 2 (Belt driven cooling system in growth chamber)	0.48	1.89	2.37
Concept 3 (Cooling plate in growth chamber peltier / cooling tubes)	0.78	1.953	2.733
Concept 4 (Cooling medium / heating coil condensate dehumidifier)	1.02	2.128	3.148
Concept 5 (Pressure dehumidifier)	0.498	1.743	2.241
Concept 6 (Absorbing dehumidifier)	0.684 (0)	1.407	2.091 (0)

Concept 7 (Adsorbing dehumidifier)	0.594	1.764	2.358
Concept 8 (Solid-polymer electrolyte dehumidifier)	0.36	2.1	2.635

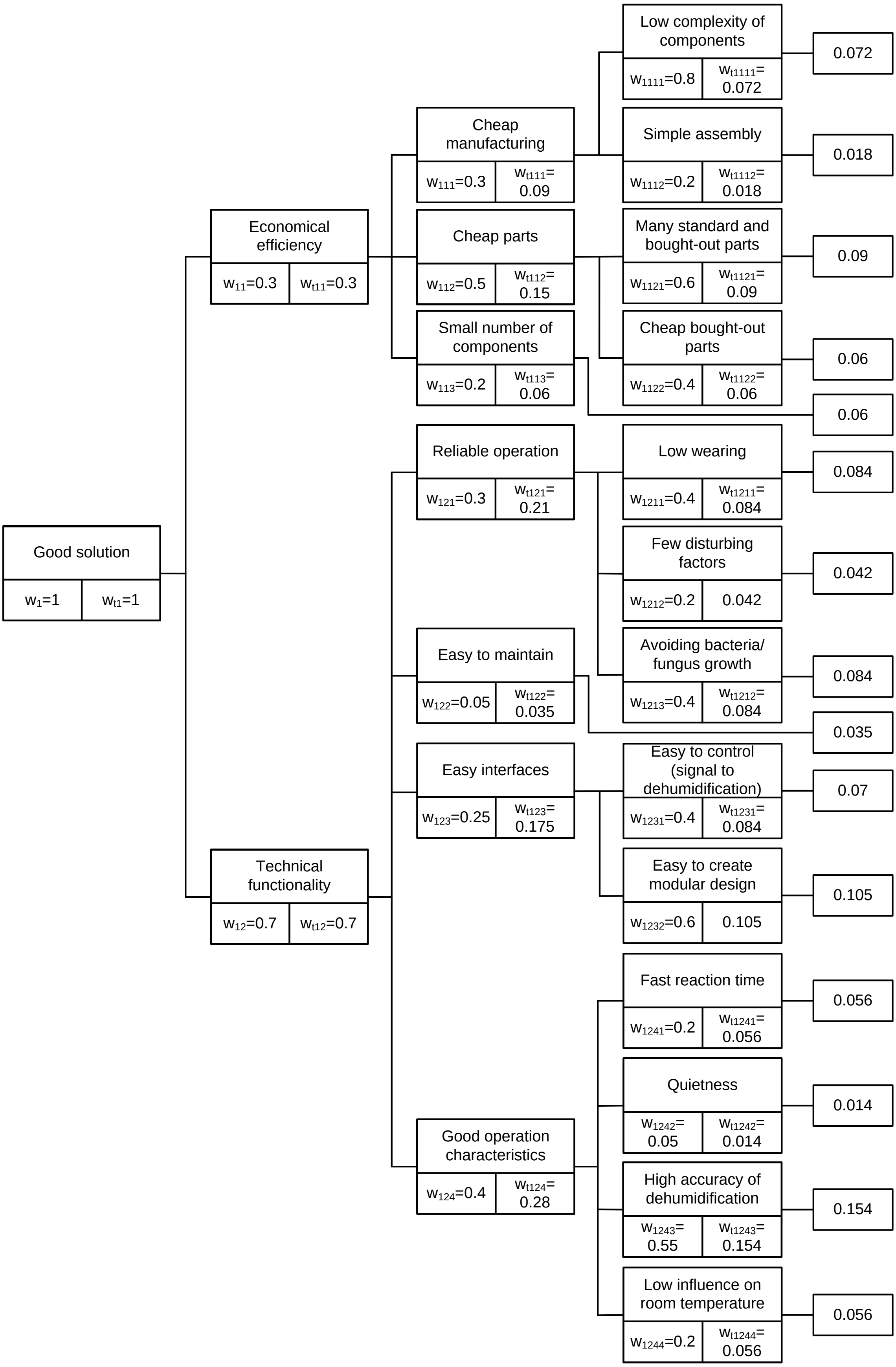


Figure 42: Objectives tree for dehumidifier evaluation

A cost/functionality matrix of the evaluation can be seen in Figure 43. Note, that in this diagram the economic efficiency as well as the technical functionality is scaled to one. The concepts with the highest overall rating can be found in the top right corner. Concept 1 (Wiper cooling system in growth chamber) got the highest technical functionality rating but is not as economic efficient as concept 4 (Cooling medium/heating coil condensate dehumidifier), which also got the second highest rating in functionality. Consequently, concept 3 (Cooling medium/heating coil condensate dehumidifier) will be realized.

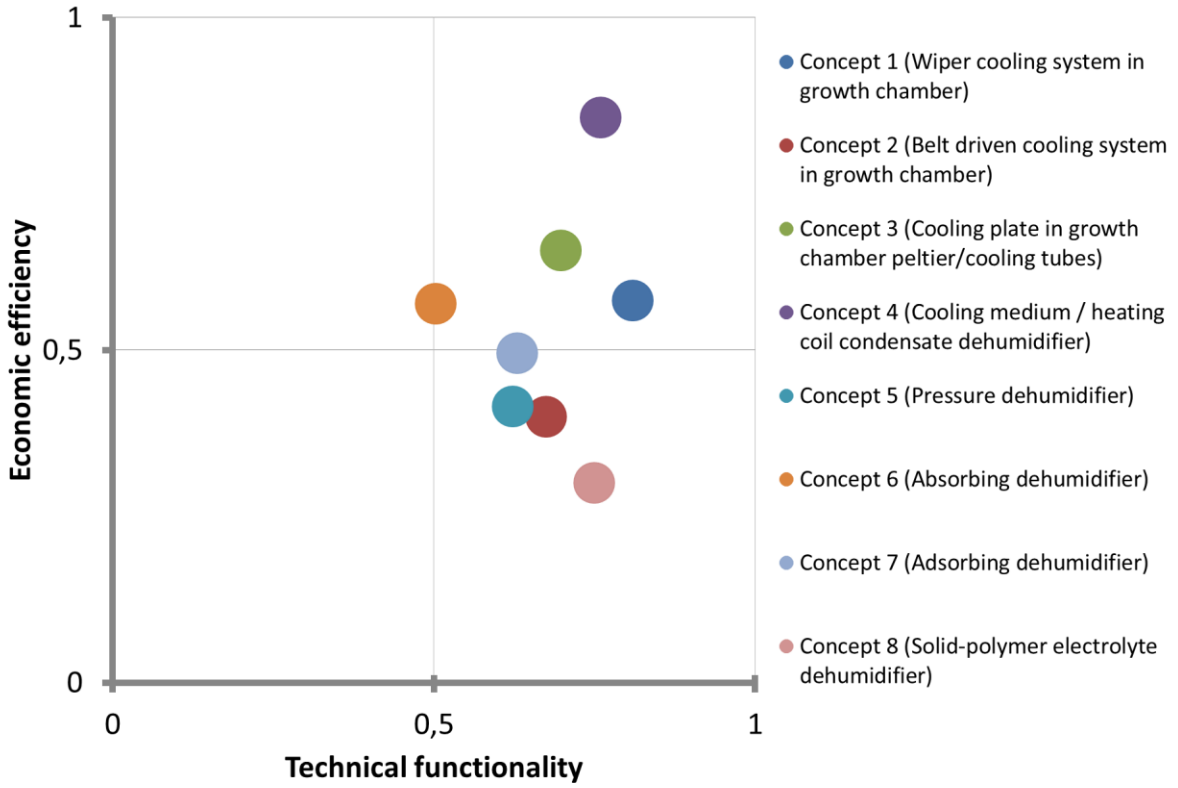


Figure 43: Cost/Functionality matrix of the dehumidifier concepts

5.2.2 Evaluation of humidifier concepts

The humidifier concepts are evaluated using the utility analysis as well. The objectives tree (Figure 44) has several similarities to the humidifier objectives tree because most general requirements are the same. However, specific criteria regarding the process of humidification are added. The costs for humidifying devices are relatively low and do not vary as much as for dehumidifiers. Therefore, a strong focus was laid on the technical functionality.

The results of this utility analysis can be found in Table 30. The corresponding Cost/Functionality matrix can be seen in Figure 45. As for the previous Cost/Functionality matrix, the axes of the diagram are scaled to one.

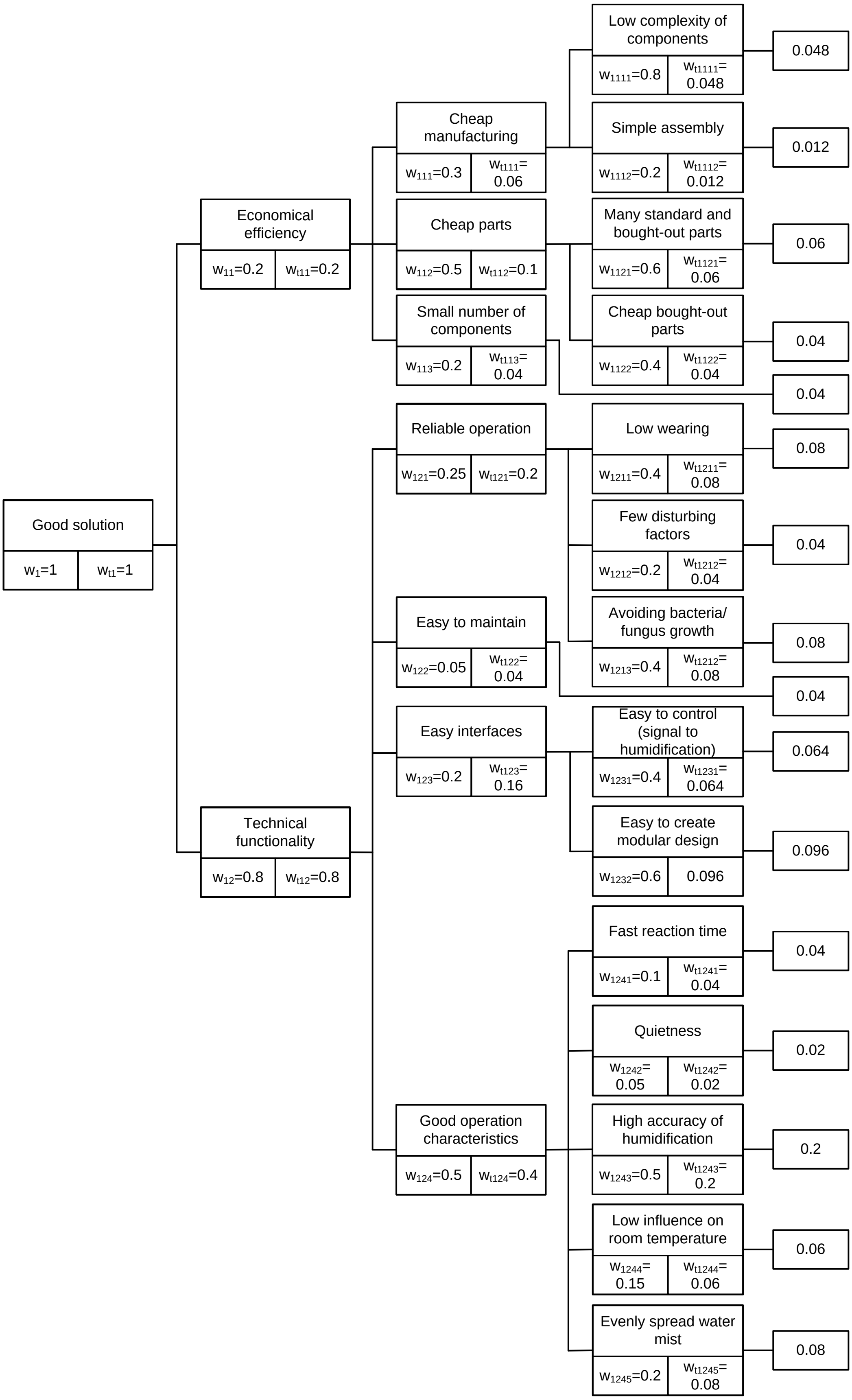


Figure 44: Objectives tree for Humidifer evaluation

Table 30: Results of the utility analysis for the humidifier concepts

Concept	Economic efficiency (max. 0.8)	Technical functionality (max. 3.2)	Sum (max. 4)
Concept 1 (Piezo humidifier)	0.6	2.704	3.304
Concept 2 (Vaporization heating coil humidifier)	0.66	2.216	2.876
Concept 3 (Vaporization electrode humidifier)	0.448	2.4	2.848
Concept 4 (Atomizing humidifier)	0.56	2.088	2.648
Concept 5 (Evaporation / adsorbing humidifier)	0.36	1.768	2.128

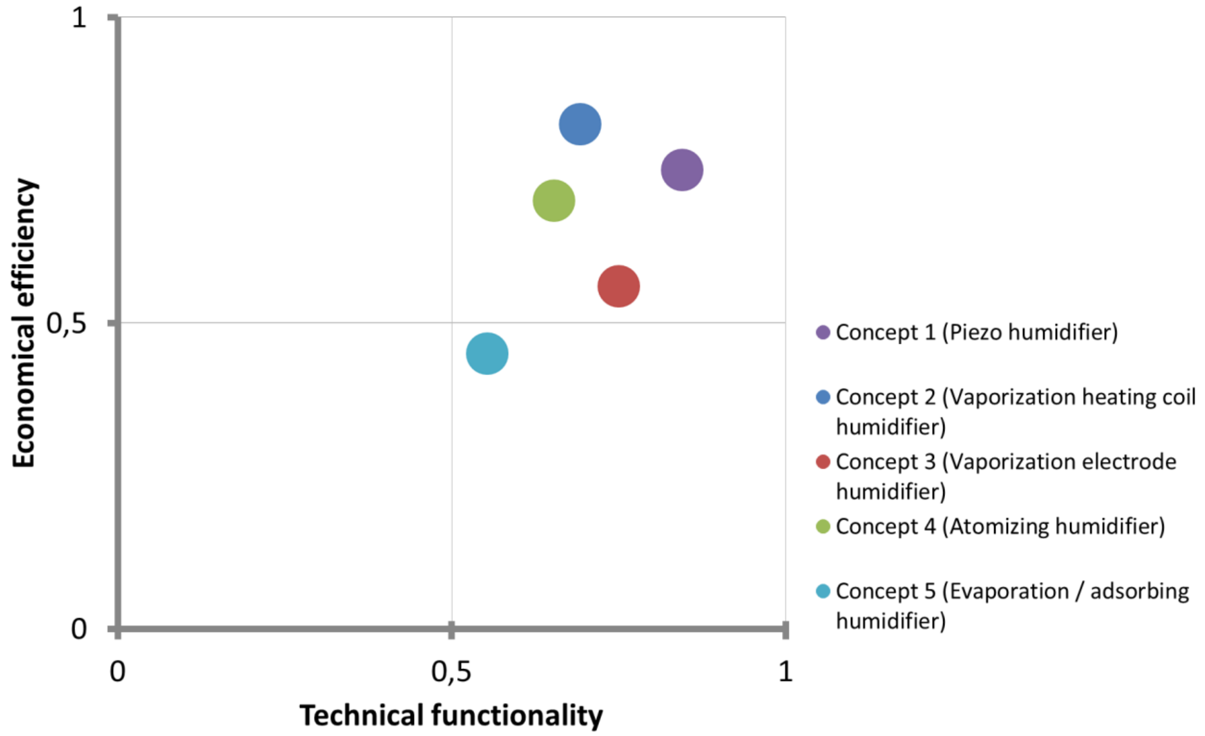


Figure 45: Cost/Functionality matrix of the humidifier concepts

The piezo humidifier is selected for implementation because of a high technical functionality and a relatively high economic efficiency. The second best solution would be either the vaporization electrode humidifier, the vaporization heating coil humidifier or the atomizing humidifier which have an almost similar technical functionality rating.

5.2.3 Evaluation of CO_2 injection concepts

The technical gas storage is selected for the EDEN Laboratory because of its feasible and reliable operation. The electromechanical components for CO_2 regulation can be obtained from aquarium suppliers. More research has to be done for successful evaluation of the other techniques described for CO_2production for small growth areas.

5.2.4 Evaluation of the humidity, temperature sensors

A capacity humidity sensor is selected because of the high precision, fast response and long term stability compared to the other sensor principles. Some manufactures offer optimized sensors of this kind for air duct installation. Since the sensor measures the relative humidity, necessarily the temperature is measured as well. This is done by PT100 elements. A second humidity measurement principle for redundancy (Langhans 1997) can be the wet bulb/dry bulb temperature sensor. A hair hygrometer should be installed in the growth chambers for direct optical verification.

5.2.5 Evaluation of CO_2 sensors

A CO_2 sensor using the non-dispersive infrared is selected because it fulfills all requirements and is the most feasible one. A second measurement principle for redundancy can be a sensor based on the photo acoustic sensor.

5.2.6 Evaluation of controllers

The AMS will be controlled using the National Instruments software LabVIEW since most components in the laboratory already focus on this solution. The software controls the ethernet based NI cDAQ-9188XT device. It has eight slots for modules such as digital/analog input, digital/analog output and other to interface the sensors and control the devices.

5.3 Concept definition

The overall concept for the AMS consists of a capacity based humidity/temperature sensor, a non-dispersive infrared sensor for CO_2 detection, a cooling coil / heater dehumidification device, a piezo based humidifier and a technical gas storage based CO_2 injection device. Supporting functions are necessary to meet all requirements. An air filter device is added to keep the system clean, condensed water is pumped to the waste water tank. A power & control device provides electric energy and establishes a connection between the LabVIEW hardware and the components.

6 Embodiment design

In the embodiment design phase, the selected concept is developed to a point where subsequent detail design can lead directly to manufacturing (Pahl 2007). This chapter describes the design of the atmosphere management system setup.

6.1 Available space and boundary conditions

The current piping layout of the laboratory is seen in Figure 46. The air duct of the growth tents is separated from the air duct of the rack system. Also, the LabVIEW control/interface unit (National Instruments CompactDAQ), the waste water tank and the osmosis water tank are spatially separated. The chilled water support station, as well as the technical gas storage and the power socket are aside the AMS.

The air ducts in the laboratory are DN 160 mm spiral ducts. The power socket is a standardized 230 VAC power socket with a 16 A fuse.

Chilled water supply

The cooling coil is cooled using a chilled fluid. Since the fluid not necessarily needs to cool down below zero degree, Gylcol-free water is chosen. In commercially available stand-alone air conditioners, typically a compressor is used. An advantage of a compressor based system is a high efficiency factor and small size. A disadvantage is the use of a special cooling medium and low flexibility to changes of boundary conditions. However, as the laboratory is a test-bed for future technologies and testing and controlling of the atmosphere management processes is a major research goal, an external 5.1 kW (chapter 3.3.3) chilled water supply (Galetti MPE-C 005CM) was purchased. The device supplies the laboratory with a continuous flow of water chilled with a temperature of 7 °C. The maximum backflow temperature has to be underneath 12 °C to stay in the operational range of the chilled water supply. The standard water volume flow is limited to 0.88 m^3/h. The connection in the laboratory is through one inch pipes. The machine can be remotely controlled. Detailed information about the chilled water supply can be found in the datasheet section in the appendix.

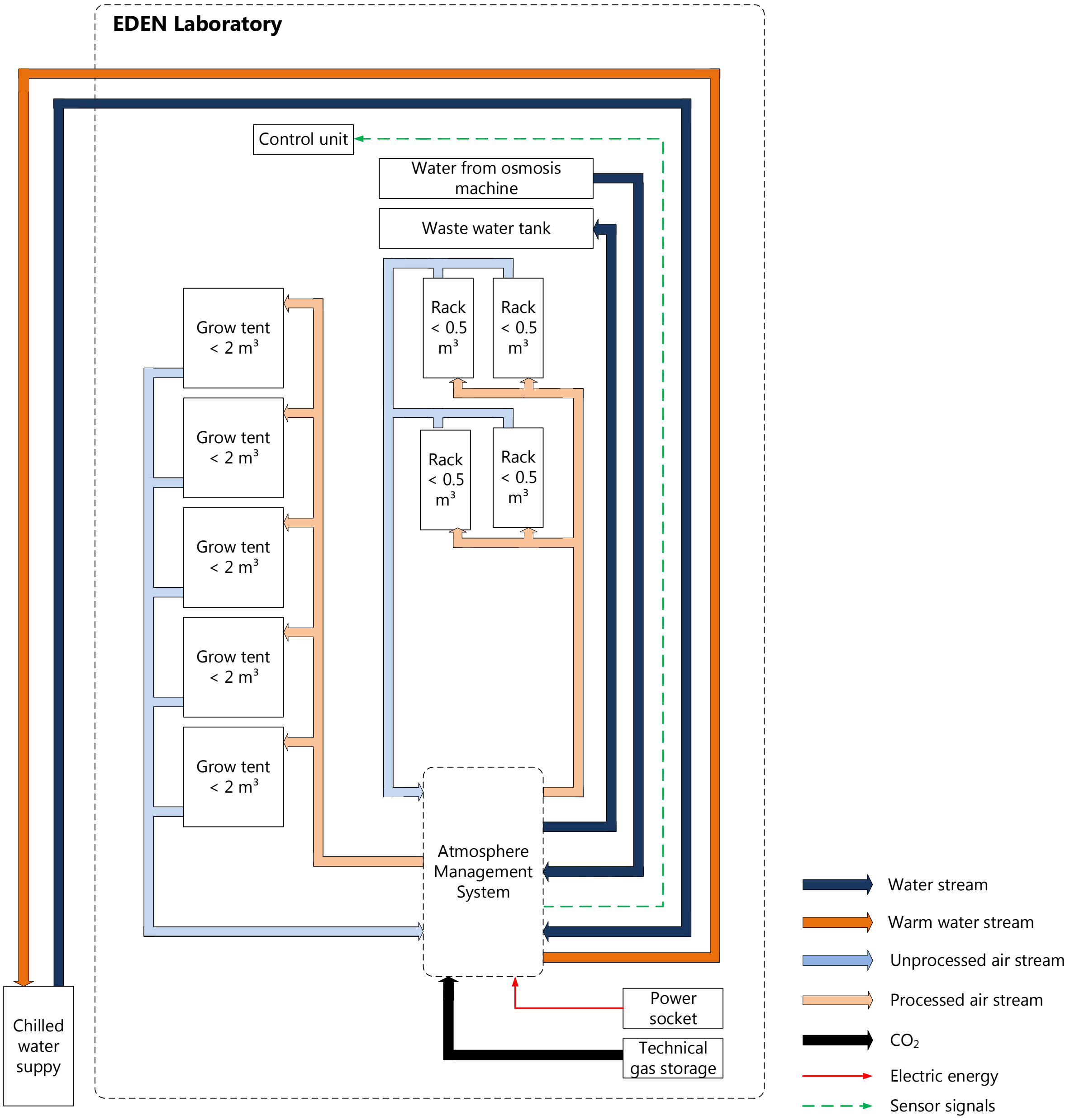
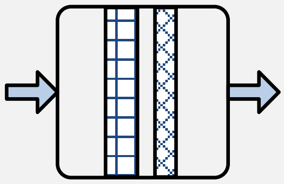
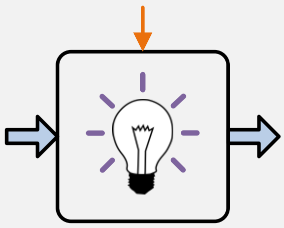
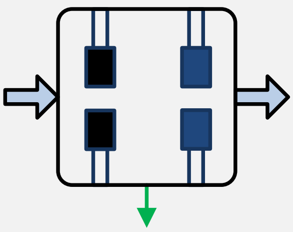
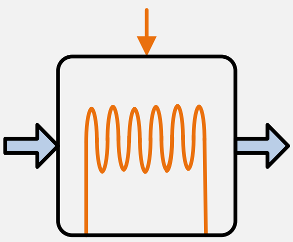


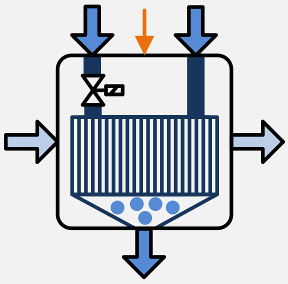
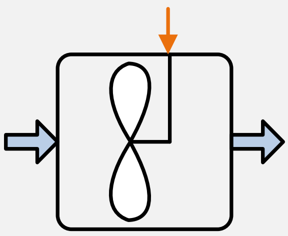
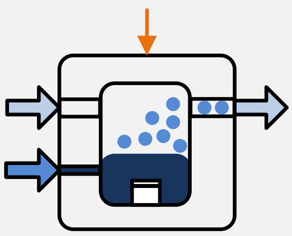
Figure 46: Schematic view of the EDEN Laboratory air piping

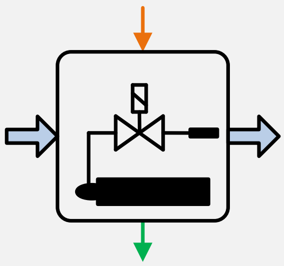
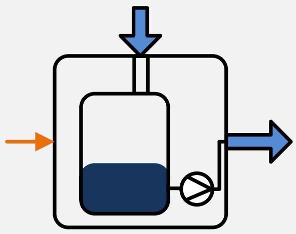
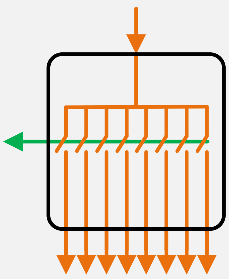
6.2 Module allocation

A list of all functions and support functions, including a task description, the requirements that apply to each module and their interfaces can be seen in Table 31. A general interface for every module is the DN 160 mm spiral duct which needs to be the same for every module for easy interchangeability. Also, the wind speed in the air duct is set to a maximum of 13 m/s, which ensures an air ventilation rate of once per minute.

Table 31: Overview of necessary modules including description, specific requirements and interfaces

Module	Description/Task	Requirements	Interfaces
Air Filter Unit 	Prevent pollution with dust particles in the AMS.	• Inspection rate < 1 /month • Preventing dust particles in the AMS	• Unfiltered humid air from growth chamber • 160 mm air duct
UVC Air Purifier 	Prevent fungi/bacteria growth in the AMS, especially at the cooling coil.	• Keep the coil fungus/bacteria free (air cleaning if possible) • Easy to change light source • Low wearing	• Filtered humid air from growth chamber • Rectangular air duct (size depending on coil) • 230 VAC (PDCU)
Sensor Array 	Measurement of humidity and CO_2 concentration.	• RH Tolerance < ± 5% • CO_2 Tolerance ± 50 ppm • At least two CO_2 and humidity Sensors for redundancy and control (Langhans 1997) • (Two different humidity measurement principles for humidity to verify results (Langhans 1997))	• Filtered humid air from growth chamber • Two analog output signals per humidity/temperature sensor • One analog output signal per CO_2 sensor
Heating Unit 	Heating the air stream.	• Heating power up to 1.3 kW	• Filtered humid air from growth chamber • 160 mm air duct • 230 VAC electricity (PDCU)

Module	Description/Task	Requirements	Interfaces
Dehumidification Unit 	Cooling the air stream and condensate separation.	• Duty of 3 kW (5 kW peak) • Dehumidifying up to 70 kg/d • Cold water in: 7 °C • Cold water out: 12 °C • Water flow rate: <0.2 l/s (cold water machine) • Air volume: 0.15 m^3/s • Antibacterial sink • Providing bacteria/fungi free environment • Preventing moisture carryover	• Filtered humid air from growth chamber • 160 mm air duct • Cold water from water chilling machine (7 °C) • ¾ inch water connectors • 230 VAC three way-valve (PDCU) • Condensed water conducting unit
Ventilation Unit 	Ventilate air through the AMS.	• Reliable use in adverse environmental conditions (High humidity/temperature/CO_2 level) • Provide air volume stream 0.15 m^3/s (=9 m^3/min, ventilation rate growth chamber: 1/min)	• Filtered (humid) air from growth chamber • 160 mm air duct • 230 VAC (PDCU)
Humidification Unit 	Increase the humidity in the growth chamber.	• Evenly spread water mist	• Filtered air from growth chamber • 160 mm air duct • Purified water from osmosis machine • 230 VAC (PDCU)

Module	Description/Task	Requirements	Interfaces
CO_2 injection Unit 	Increase the CO_2 concentration in the growth chamber.	• Injection of up to 0.5 kg_{CO2}/d • Closing CO_2 valve in case of critical concentration • Closing CO_2 valve in case of power loss • Visualization of the CO_2 valve state	• Technical gas storage (W 21.8x1/14") • Filtered air from growth chamber • 160 mm air duct • 230 V AC Electricity
Condensed Water Conduction Unit 	Conduct water from cooling coil to osmosis tank/osmosis machine.	• Providing bacteria/fungi free environment	• Chilled water from cooling coil • One inch water tube • Water purification system • 230 VAC electricity (PDCU) for pump
Power Distribution and Control Unit (PDCU) 	Control the power sources of all electrified modules and establish connection between the LabVIEW interface and the components of the AMS.	• Switching power on and off of all electrified devices through LabVIEW • Provide all electrified devices with necessary power • Fuses for all electrified devices • Emergency shutdown button	• LabVIEW Module NI 9472 (8 channel 24 VDC Output) • LabVIEW Module 9220 (4 channel 0-10 VDC Input) • 230 VAC Source • 230 VAC Output

6.3 Module sequence

The developed order of the components can be seen in Figure 47. The air filter unit is placed at the beginning of the AMS to prevent any further units from dust and contamination. The sensor array is placed behind the filter to sense the current humidity and CO_2 concentration in the tent. After the sensors, a ventilation unit is placed. The UV lamp is placed before the cooling coil, to prevent pollution. The cooling coil not only cools the air but also dehumidifies, so it needs to be placed before the heater to ensure a low temperature and high humidity. The humidifier is placed behind the cooling coil and the heater for maximum flexibility even though the air stream temperature decreases after injecting water droplets due to latent heat transfer which requires increased control effort. However, the humidifier could also be placed before the cooling coil to maintain a constant humidity or before the heater. The CO_2 injection unit is the last unit, because an increased amount of CO_2 in the air may increase the corrosion rate of the following modules. The components will be arranged in a U-shape, since the air ducts in the laboratory as well as in the analogue testing site are located at the ceiling.

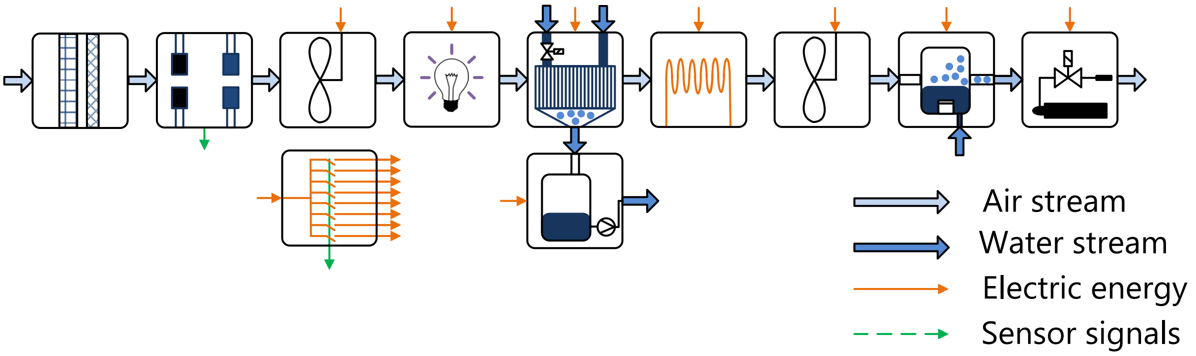


Figure 47: Order of the components in the AMS

6.4 Module design

6.4.1 Air filter unit design

Two air filters are used to filter particles and prevent pollution in the system (Figure 48). Air filters are divided in three groups depending on the filtered particle size. DIN EN 779 covers the coarse dust (> 10 µm) and fine particle (1 µm – 10 µm) filter. EN 1822-1:1998 covers the extra-fine particle filters (< 1 µm). Extra-fine particle filters are not used because the pressure drop would be too high. Instead, an UVC coil is installed in the air stream to destroy particles of this size, which are mostly fungi spores, bacteria and viruses. A list of different filters and their typical application can be found in the Appendix.

The two selected filters are a G4 and a F7 filter, since these are standard for air conditions. The filters are placed inside a modular box which can be integrated in the air stream easily.

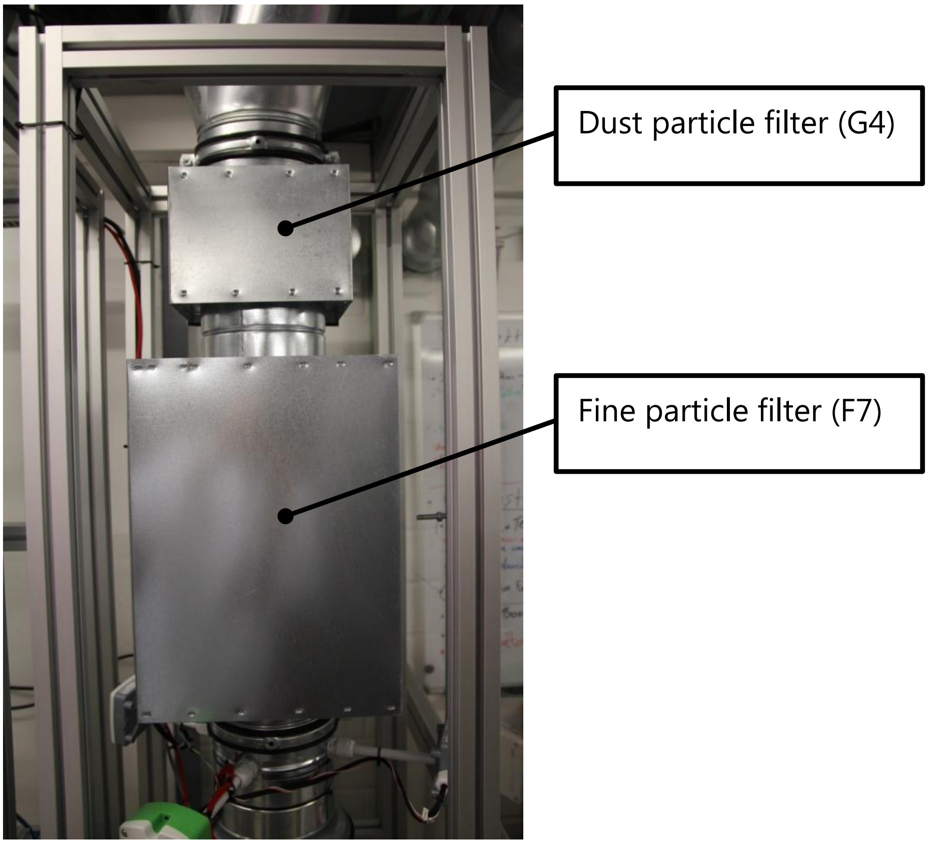


Figure 48: Air filter

6.4.2 Sensor array design

The humidity sensor EE 160-HT3xxPBB-T004M from the company E+E fulfills the required specifications described in chapter 4. The measurement principle for humidity is capacity based and for temperature a PT100 is used. The accuracy is about 2.5% RH at 20 °C, the measurement range is 10-95% RH, the output signal is proportional to 0-10 V and it has a specialized housing for in duct installation.

The CO_2 sensor EE16-FT3A21 from the company E+E fulfills the required specifications for measuring the CO_2 concentration. The measurement principle is NDIR and the accuracy below 2000 ppm is 50 ppm. Long term stability is typically 20 ppm per year. The output signal is also proportional to 0-10 V and it has a specialized housing for in duct installation. Detailed information about the sensors can be found in the datasheet section of the Appendix. Two sensors of each kind are used to measure relative derivation and ensure a reliable operation. The sensors are integrated circular in one part of the 160 mm air duct to provide the modular design (Figure 49).

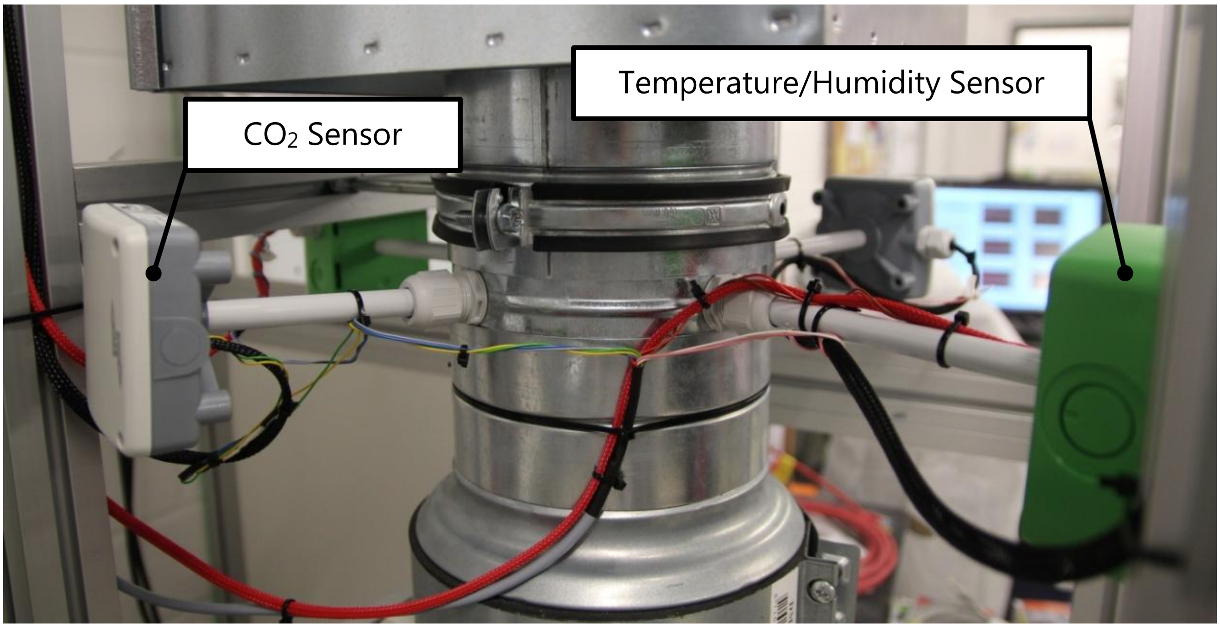


Figure 49: The sensor array (Humidity/Temperature sensor = green, CO_2 sensor = grey)

6.4.3 Ventilation unit design

Formula 9 is used to define the minimum air flow rate. The total growth chamber capacity (V) is multiplied with the air ventilation rate per minute (x). For ventilating the estimated air volume of 9 m^3 per minute, the formula solves an air volume stream of 540 $\frac{m^3}{h}$.

$$\dot{V} = V * x * 60 \left[\frac{m^3}{h}\right] \quad (9)$$

The fans already available in the laboratory (S&P Silent 1000 ventilators) can deliver up to 1100 m^3/h each. The ventilators have two modes each, 1100 m^3/h and 800 m^3/h. The following resulting air mass flows can be achieved:

- 800 m^3/h,
- 1100 m^3/h,
- 1600 m^3/h,
- 1900 m^3/h,
- 2200 m^3/h.

A security margin of four is included, providing safety against pressure drops due to flow resistance. The noise for one ventilator is declared as 21 dBa maximum in a distance of 3 m, making the device relatively silent. Since the Ventilators have a 200 mm air duct connection, additional profiles which reduce the diameter to 160 mm are added.

6.4.4 UVC air purifier design

UVC light destroys bacteria, spores and viruses. Therefore the dose is of high importance because it gives, together with the UV irradiation dose table (Appendix), information on how many bacteria, spores or viruses are destroyed through the lamp. The UV dose is calculated with the following Formula:

$$UV - Dose = \frac{Intensity * Time}{Surface} \left[\frac{\mu W * s}{m^2}\right]. \tag{10}$$

The UVC air purifier is selected in close cooperation with a SPC Coils engineer, who uses a design program offered by the UVC lamp distributer Sanuvox. The input information is the previously determined coil dimension, the distance between the coil and the lamp and the number of lamps. The average UV Irradiation intensity of 2712 $\frac{\mu W}{m^2}$ which is distributed by the lamp kills, according to the lamp selection program, all relevant bacteria and spores in a short amount of time. The lamp datasheet with additional information can be found in the appendix. A custom frame is manufactured in order to integrate the lamp in air stream (Figure 50).

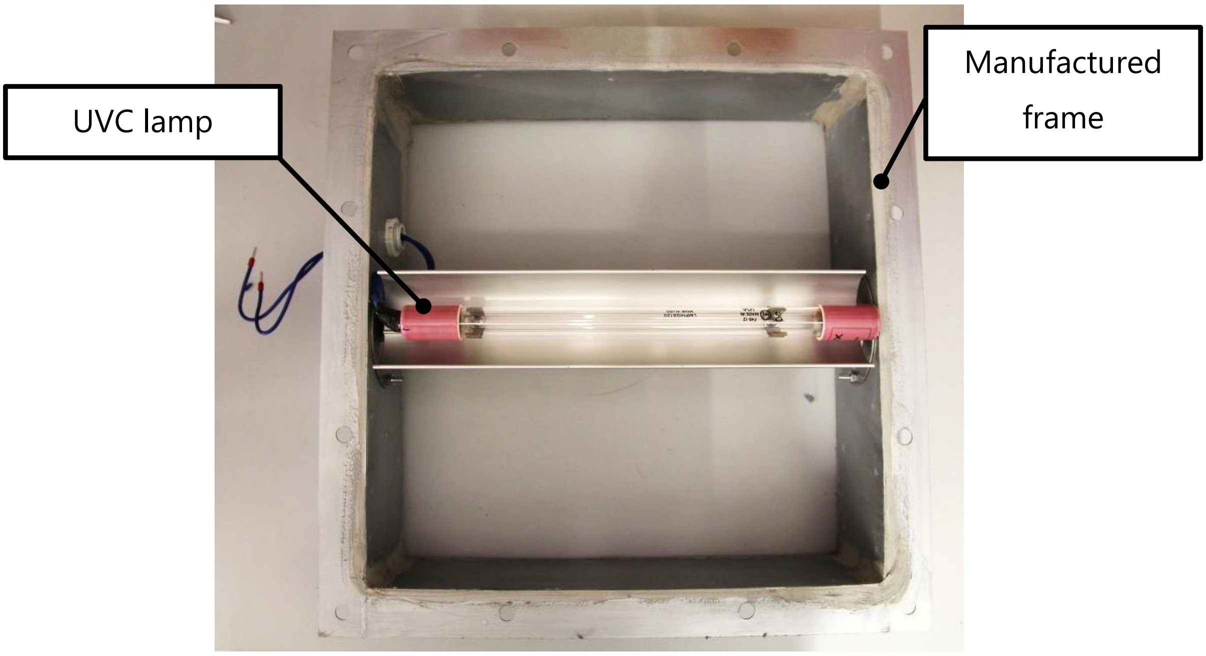


Figure 50: UVC air sterilizer inside manufactured frame

6.4.5 Dehumidification unit design

The main component of the dehumidifier is the cooling coil. The coil consists of tubes, fins and housing. Fins are thin pieces of sheet metal, which are aligned horizontally to the air stream for maximum heat transfer. They are connected via mostly copper tubes that provide the cold water flow. The housing protects the fins from external influence. Several interconnected parameters specify the coil which makes an iterative design process necessary. Most cooling coil companies offer a calculation program which directly shows the effect of a parameter variation. The software "SPC Coils 6.8" is utilized to iterate the cooling coil design (digital Appendix). Table 32 shows a selection of design tips for cooling coils regarding typical parameters, a more detailed list can be found in the appendix.

Table 32: Design tips regarding certain coil parameters

Parameter	Design tip
Coil dimensions	• Limited height 750 mm (condensed water in the upper part influences lower part) • Long and narrow design is cheaper (2:1 ratio) • Small depth is cheaper
Face velocity	• Face velocity should be between 1.5 m/s and 2.5 m/s • If face velocity is more than 2.5 m/s water droplets are more likely to get carried over • Face velocity below 1.5 m/s leads to an uneven air distribution
Water temperature	• Given by cold water supply – usually between 7 °C in and maximum 12 °C out
Coil dimensions	• Long and narrow design is cheaper
Fin spacing	• Usually between 236-551 FPM (Fins per meter) • Close fin spacing is the most economical one but increases dirt collection and pressure drop
Fin surface	• A rippled fin surface increases heat transfer at same size around factor two compared to a louver fin surface but also the pressure drop is increased by that

Fin thickness	• Thicker fins ensure longer lifespan (assumption)
Fin coating	• For salt air and mid-city applications longer life can be obtained by additional coating – 30% more expensive
Water tube design	• Water velocity above 0.3 m/s for turbulent flow • Water velocity below 1.5 m/s to avoid erosion • Water pressure drop normally <30 kPa

Table 33 shows the design of the cooling coil regarding the requirements. The relevant parameter column gives information about which parameters affect the design. The selected cooling coil is capable of cooling an air stream of 25 °C dry bulb temperature and 70% RH to 15 °C dry bulb temperature and 100% RH continuously if ventilated once per minute. Heating the air to 21 °C dry bulb temperature will result to a relative humidity of 68%. The re-heating to 25 °C and 70 % RH inside the growth chambers equals an average water production of tomato plants on 13.6 m^2 crop area and a heat dissipation of 2.8 kW through lamps (Figure 51).

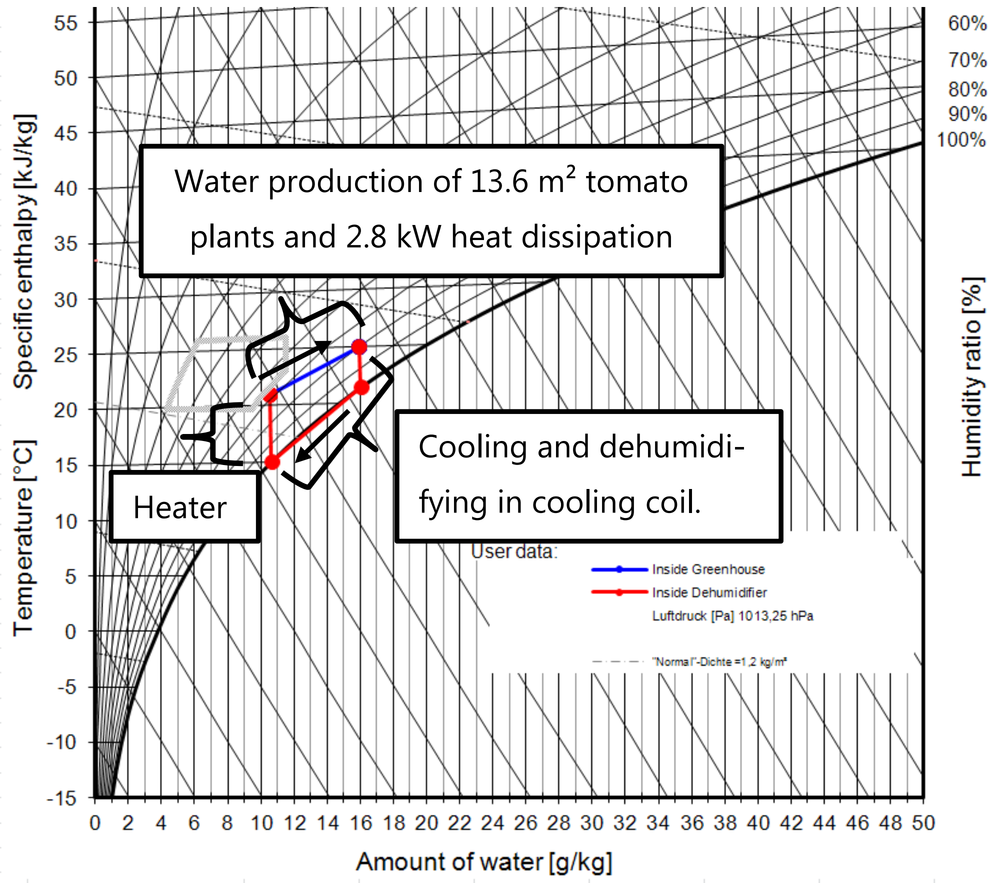


Figure 51: Mollier h-x-diagram with selected cooling coil

Table 33: Cooling coil design regarding requirements and design tips

Requirement	Relevant parameters	Design
Coil load up to 3.6 kW	• Coil dimensions • Face velocity • Water temperature • Water tube design	• Rippled fin surface • Face height 308 mm • Cold water supply up to 5 kW • Coil duty with all specifications 3.72 kW (Exchange 1/minute)
Water supply 7 °C in, maximum 12 °C out, Flow rate < 0.244 l/s	• Water tube design	• Number of tubes height: 8 • Number of tubes: 8 • Tube diameter 12 mm • Flow rate: 0.178 l/s • Water velocity: 0.39 m/s • Water pressure drop 8.155 kPa • Water connectors: 3/4"
Air exchange 1/minute (Wind speed in 160 mm tubing = 13 m/s)	• Coil depth (pressure drop) • Face velocity	• Face dimensions 308 mm * 300 mm • Face velocity ~1.6 m/s • Pressure drop 59.5 Pa
No droplet carryover	• Face velocity	• Face velocity ~1.6 m/s
Small size	• Face dimensions • Depth • Fin spacing • Fin surface	• "Cube" shape, more expensive but other requirements are more important • Rippled fins
Bacteria/Fungi spore free	• Fin spacing • Fin material	• Fin spacing selected: 354 FPM • Additional air filter • Additional UVC sterilizer
Low pressure drop	• Fin spacing • Fin surface	• Rippled fins to reach dimension goals
Maintenance free	• Fin material • Fin coating	• Blygold coating • Fin spacing selected: 354 FPM • Thick finns: 0.25 mm • Additional air filter

		• Additional UVC sterilizer
Safe condensed water transport	• Drainpan style • Drainpan material	• Sloped drainpan • Stainless steel drainpan

The coil datasheet can be found in the appendix. The coil is controlled using an electromechanical two-way valve. The valve is integrated in the water stream and conducts chilled water through the coil if opened. The water flow stops if closed. To integrate the cooling coil in the 160 mm air ducts, custom adapters are manufactured according to manufacturing drawings which can be found in the appendix. The assembly of UVC lamp and cooling coil can be seen in Figure 52. The chilled water inlet cannot be seen in this picture.

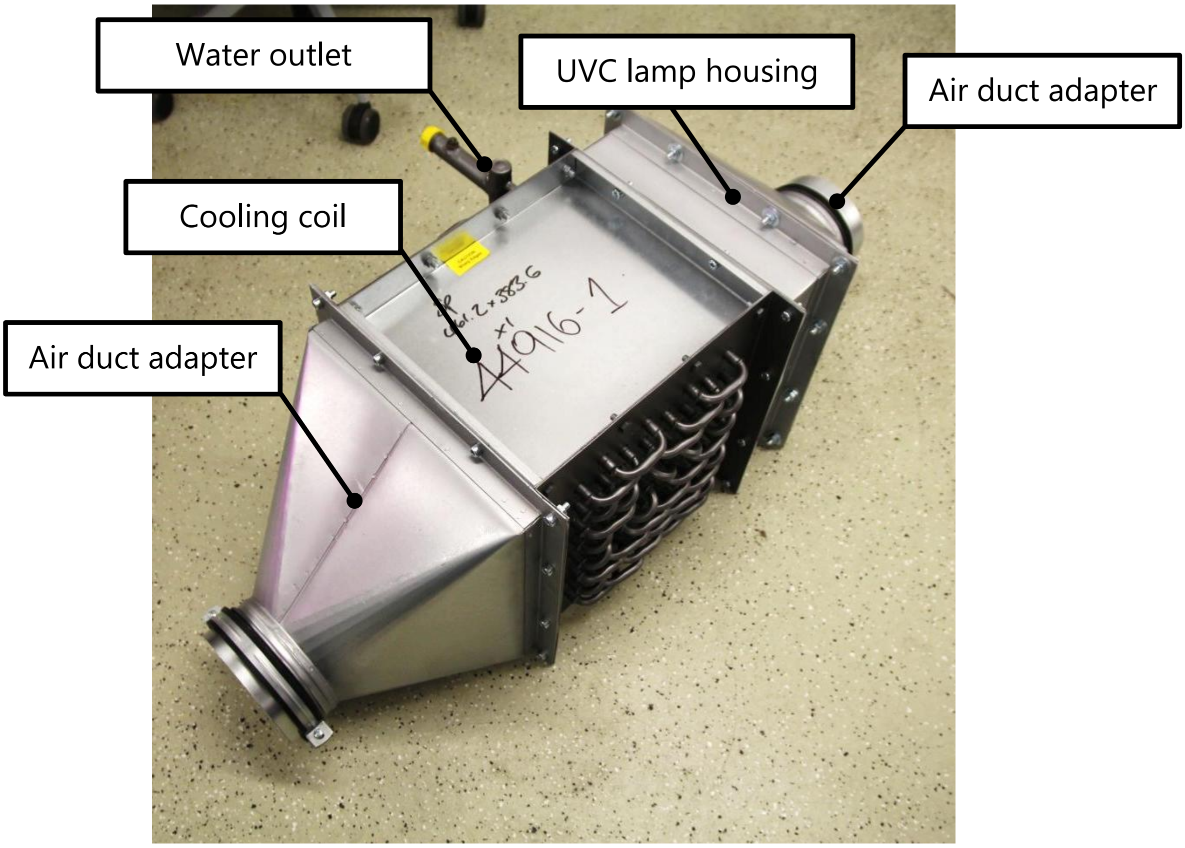


Figure 52: Cooling coil with UVC lamp and air duct adapters

6.4.6 Condensed water conduction unit design

The condensed water conduction unit consists of a water tank attached to the dehumidification device. A water pump with level switch is integrated in the tank to start pumping the water to the waste water tank once a certain level is reached. A water filter and an UVC lamp for sterilizing the water might be a useful addition in future application but is not considered in this design.

6.4.7 Heating unit design

A heating device is necessary to heat the air stream. To raise the temperature from 15 °C dry bulb to 21 °C dry bulb of 540 kg/h air, a total energy of 0.89 kW is needed. The heating is done electrically via resistive coil. The selected device can be integrated in a 160 mm air duct and has a heating capacity of 1.2 kW, which gives a security margin of 1.35 (Figure 53).

Figure 53: Electric air heater with 160 mm air duct connection

6.4.8 Humidification unit design

It is reasonable to set up a mass balance around the growth chamber to determine the leakage flux, in order to determine the necessary humidification rate. Unfortunately, the leakage flux from the growth tents to the surrounding laboratory is not known yet, so for dimensioning a different boundary condition is chosen. In case of a constant humidity and temperature in the laboratory and the growth tents, no leakage fluxes occur (unless the door is opened which shall be neglected in this calculation).

Regarding the theoretical case of 50% RH and a temperature of 20 °C, the humidifier should be capable of releasing as much water to raise the relative humidity to 70% in the whole laboratory, neglecting latent heat transfer which would reduce the temperature at the same time. For this worst case scenario, the following formula can be used. The total amount of water transpired by plants per day ($\dot{m}_{Water}$) is calculated by multiplying the amount of water per kg air (x_i) with the air volume in laboratory ($\dot{V}$, ventilated once per hour) and the air density at certain state ($\rho_{air,20°C}$).

$$\dot{m}_{Water} = (x_1 - x_2) * \dot{V} * \rho_{air,20°C} \;\; [\frac{g}{h}] \tag{11}$$

A relative humidity of 50% and 20 °C equals 7 g water per kg air. A relative humidity of 70% and 20 °C equals 10 g water per kilogram air. 3 g water which needs to be added to the air stream per kilogram air.

An air volume of 78 m^3 which is ventilated once per hour equals an air mass stream of 93.6 kg at 20 °C. As a result, 280.8 g water need to be released into the air to reach 70% RH in the laboratory. The selected humidifier has a distribution rate of 330 ml/h giving a security factor of 1.18.

6.4.9 CO_2 injection unit design

The components of the CO_2 injection unit can be seen in Figure 54. A common CO_2 cylinder has a working pressure of 50-250 bar. Since CO_2 is liquid between -56.6 °C and +31.1 °C at a pressure of more than 5.2 bar, the pressure needs to be reduced below 3 bar (because of the security valve) to have gaseous CO_2 and an adequate working pressure. An electromechanical valve, operating with 230 VAC, conducts the gas flow through a back pressure valve to a fine adjustment valve. To inject CO_2 in the air stream, a standard 1/4" plastic tube is inserted into the DN 160 mm air duct of the AMS through a modified 1/4“ pipe connector (Figure 55). The description of the pressure reducer and safety instructions can be found in the datasheet section of the appendix.

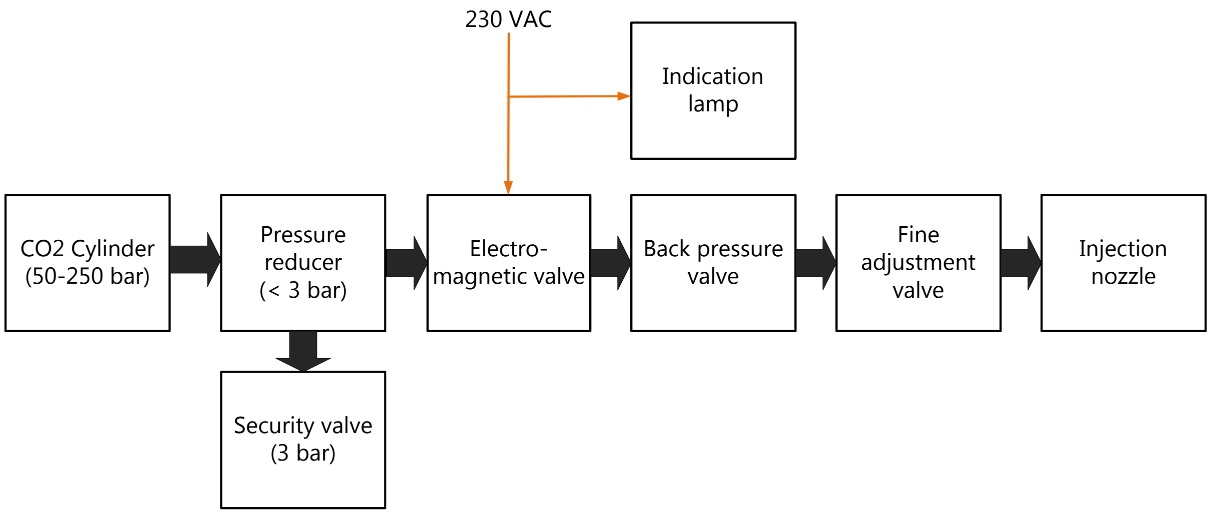


Figure 54: Components of the CO_2 injection unit

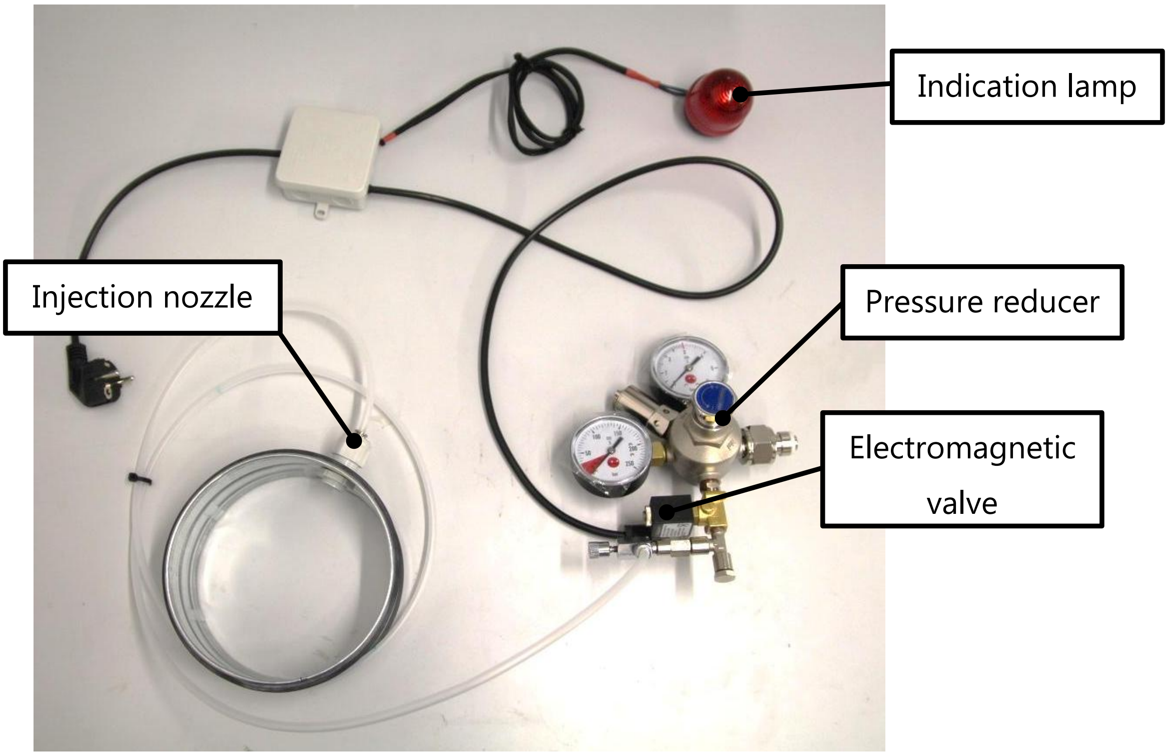


Figure 55: The CO_2 injection unit

6.4.10 Power distribution and control unit design

The electric design of the Power Distribution and Control Unit can be seen in Figure 56. All components except the sensors and the control unit are located on 35 mm rails which are directly attached to the AMS. Electrical power, which is distributed through a 230 VAC power socket is conducted through an on/off emergency switch. Its power is then split up to a fused 24 VDC power supply to deliver the necessary voltage for the sensors and eight remotely controlled power sockets. The eight power sockets are protected through eight fuse switches, which can also be used to manually disconnect the power socket. Eight relays are used to remotely control the power sockets. The selected relays need 24 VDC supply voltage for switching. The peak switch current is specified with 10 A, which is sufficient even for high power consumers such as the air heater (around 6 A) or the ventilator (0.5 A). The 24 VDC supply voltage for the relays is provided by the NI 9472 module. This module is able to switch on eight 24 VDC power sources through the LabVIEW software respectively controlling the power sockets. The 24 VDC for the relays are conducted through a regular cat 5 cable to reduce the amount of cables. The sensors, which are selected to have a 0-10 V electric output signal, are connected to the NI 9220 analog input module. To reduce the influence of parasitic induction, a shielded signal wire is used.

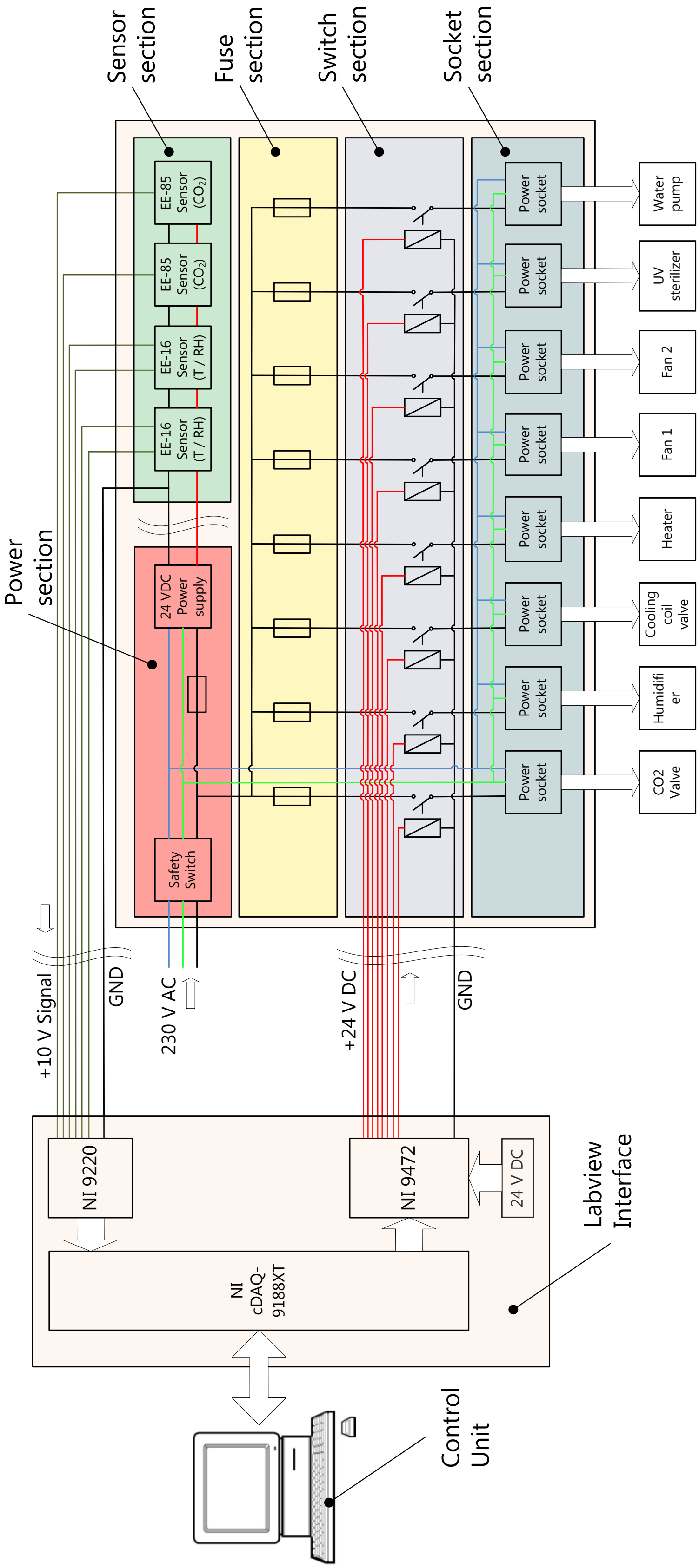


Figure 56: Wiring diagram of the Power Distribution and Control Unit

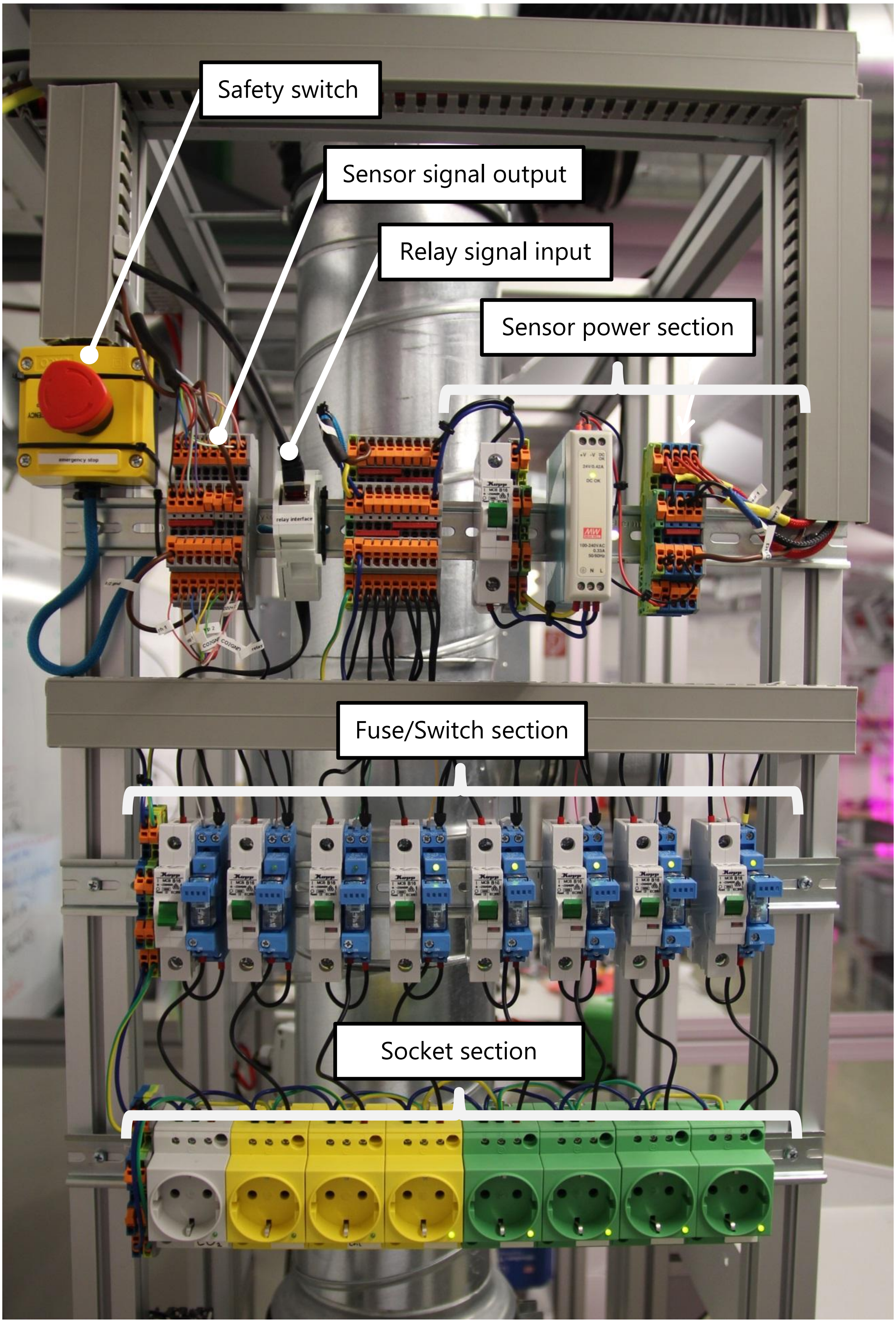


Figure 57: The Power Distribution and Control Unit

6.5 Prototype setup

ITEM aluminium profiles are used to construct a frame and to integrate the components (Figure 58). Flex tubes are used at the air inlet and outlet. The shape of the prototype was changed from an ideal U-shape in order to easily change and maintain the components.

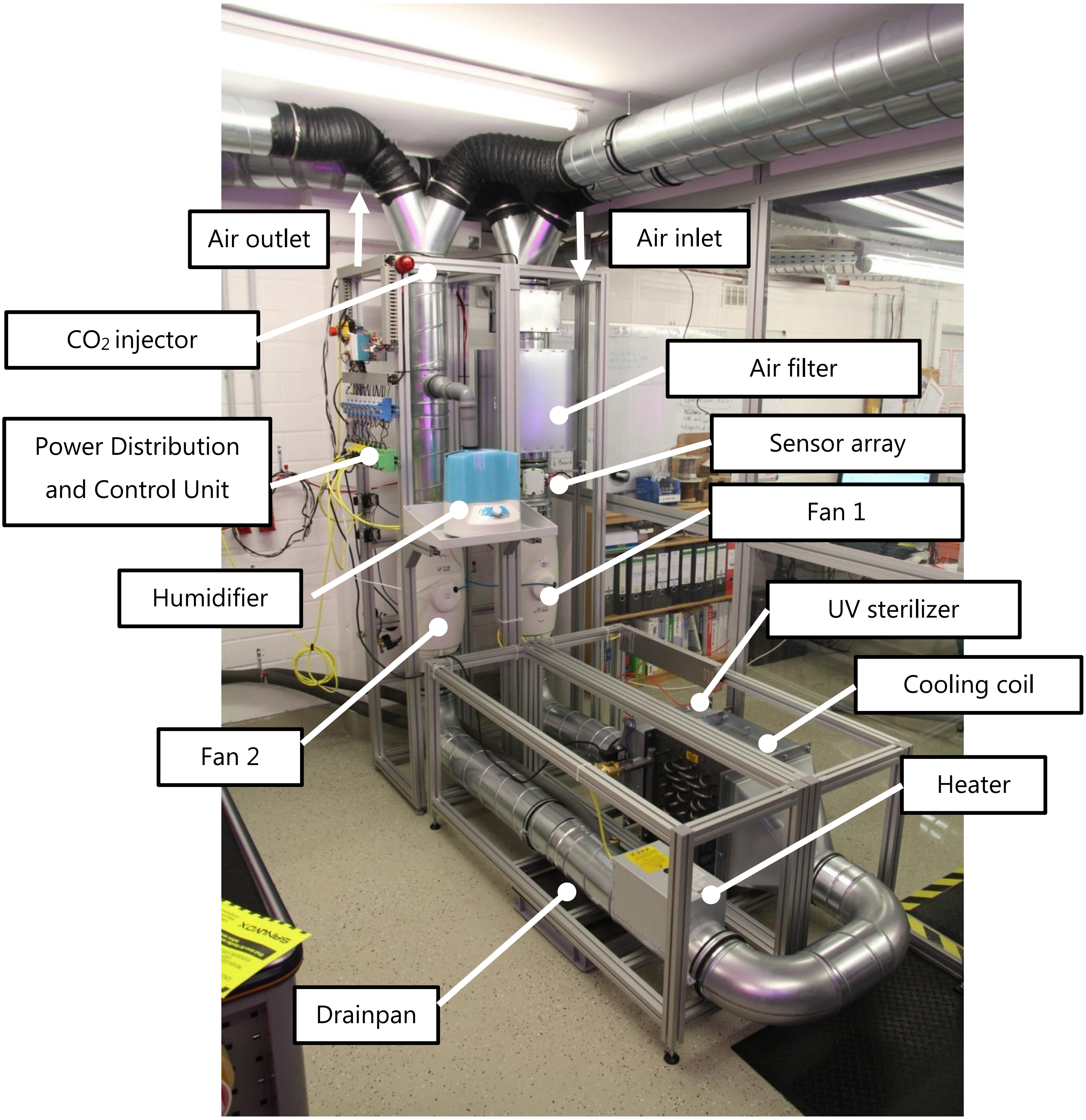


Figure 58: Prototype of the Atmosphere Management System

6.6 Control program

The software to control the AMS is LabVIEW. As mentioned in the previous chapter, the sensors provide the current state of humidity, temperature and CO_2 in the upstream. The power socket and hence the devices are activated depending on the sensed values and a given threshold. A principle drawing of the temperature control can be seen in Figure 59. The continuous sensor signal crosses the limit for maximum temperature and the power socket that controls the cooling coil valve is activated. The valve is closed once the temperature decreases below the threshold.

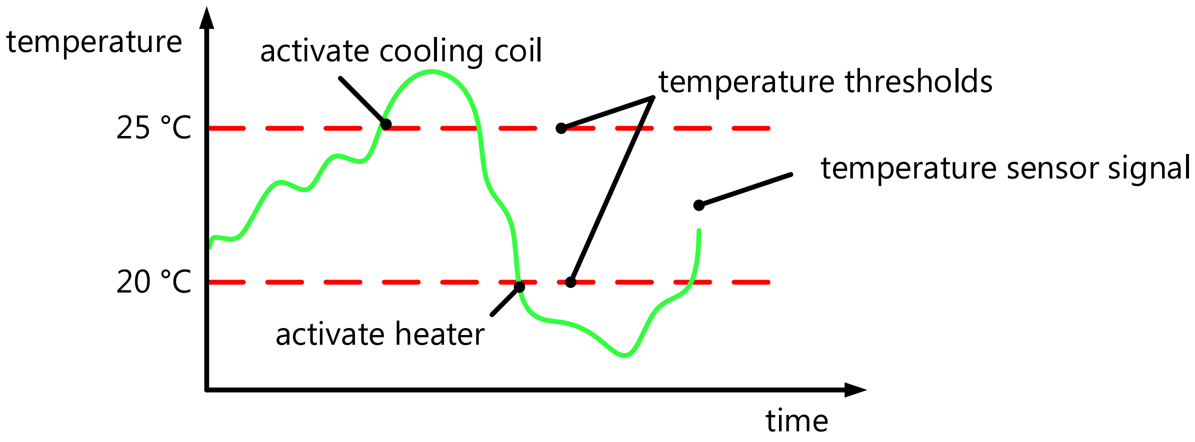


Figure 59: Temperature control principle drawing

The same principle is used for all control variables:

- Temperature too high or humidity too high: open cooling coil valve
- Temperature too low: activate the heater
- Humidity too low: activate Humidifier
- CO_2 concentration too low: open CO_2 valve

A graphical user interface is implemented in order to manually test the components, enter the thresholds and monitor the sensor signals over short and long term periods (Figure 60). Green buttons indicate which component is currently activated. A detailed description and structure of the LabVIEW program can be found in the appendix.

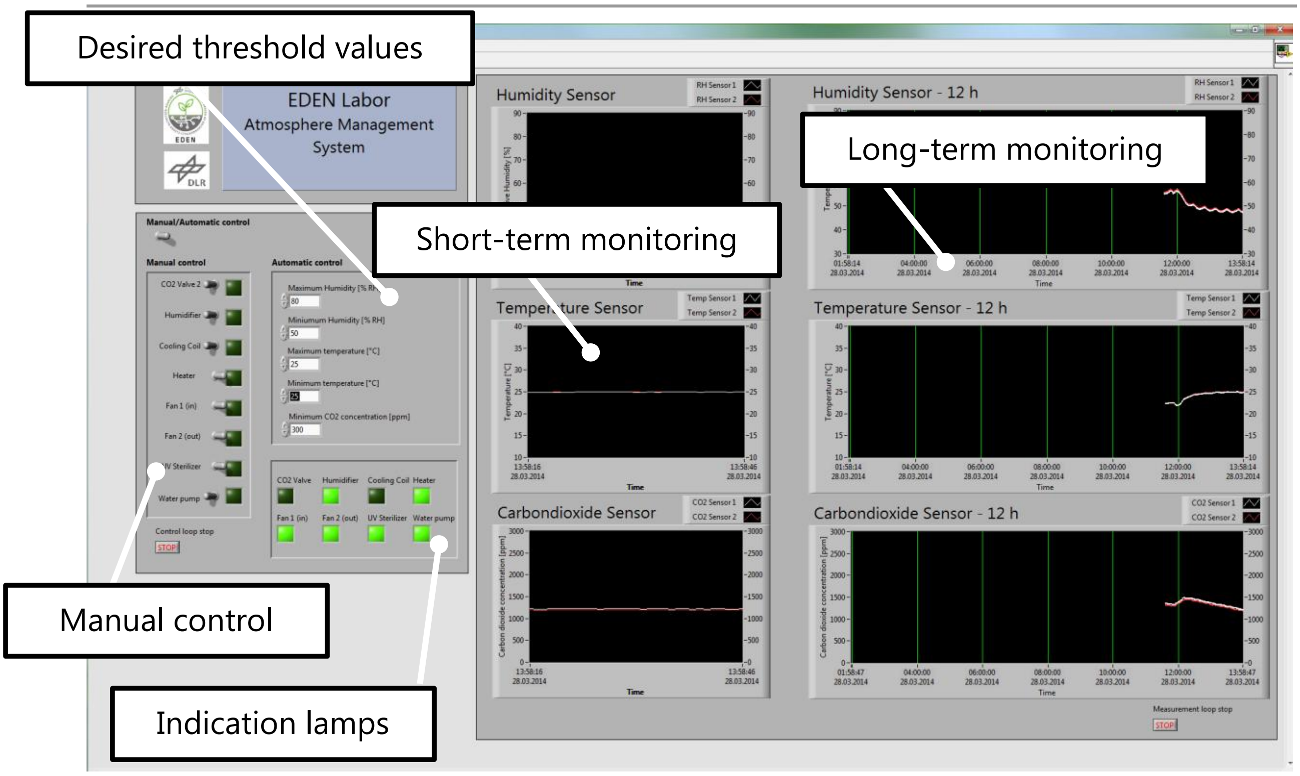


Figure 60: Graphical User Interface of the AMS control program

6.7 Discussion

Humidifier redesign

In the current setup, the humidifiers steam output is directly connected to the air duct. However, high static pressure inside the air duct pushes the generated water droplets through air gaps of the humidifier out of the system. Integrating the humidifier including water supply into the air stream could be a possible solution for further iterations.

CO_2 injection through breathing

It was observed that the CO_2 concentration increases rapidly with number of people working in the laboratory. A typical peak level is 1500 – 2000 ppm at the end of a working day with no plants inside the laboratory. The CO_2 concentration decreases during night due to diffusion to other rooms. Breathing needs to be taken into consideration if calculating the amount of CO_2 needed for active CO_2 fertilization.

Influence of isolated tubing

The air ducts are currently not isolated. If the temperature in the laboratory is below the dew point of the ventilated air, water might condense inside the ducts. Standing water should be avoided to reduce the risk of bacteria and fungi growth. Hence, isolating the air ducts is highly recommended for future design iterations. Also, the cooling coil tubing which is currently exposed to the laboratory should be isolated to prevent water condensing from the ambient air.

Post-Processing the condensed water

The condensed water inside the cooling coil is classified as grey water, which means it can be used to flower plants after it has been post-processed through mechanical or biological systems. It should not be sprayed before it is purified since pathogens in the water can infect the lung through aerosols. The current prototype uses a water pump with an integrated level switch to pump the water. In further iterations, a water filter and a UV sterilizer should be used for post-processing.

Air pressure equilibration in growth chambers

The air ducts which connect the growth chambers to a unified air stream are not equilibrated in the current setup. This results in a faster air exchange in the growth chambers close to the Atmosphere Management System. Countermeasures could be air regulators which are installed on both growth chamber air inlets and outlets.

Sensor malfunction alarm

The sensor array consists of two humidity/temperature sensors and two CO_2 sensors. The reason for this is redundancy of the system. Currently, both sensors measure the same values within a relatively small error margin. A function in the LabVIEW program which compares the values between both sensors continuously and outputs an error message once a gap is detected would benefit the safety of the system.

7 Conclusion

The goal of this thesis to find a way to regulate the atmosphere in terms of humidity, temperature and CO_2 concentration in an environmentally closed growth chambers was achieved. A concept for a modular device that can be integrated in a centralized air stream is the result of an iterative design process described in the previous chapters.

In short, the solution consists of the following modules:

- Cooling coil for cooling and dehumidifying,
- Electric heating device,
- Piezo-based humidifier,
- CO_2 injector,
- Two filters and a UVC air sterilizer to protect the system from dust, bacteria and fungi,
- Sensor array to measure humidity, temperature and CO_2 concentration,
- Power control system with LabVIEW interface and control software,
- Air ventilators.

The modules are chosen because of their superior results in terms of functionality and cost efficiency compared to alternative solutions during the evaluation process. The modular design provides the possibility of adapting the system to analogue testing sites with low effort through up- and downscaling of the independent sub systems.

All sub systems of the solution are manufactured and compiled in a working prototype in the EDEN Laboratory. The functionality of the system and the control is verified by various tests. Potential improvements are identified and proposals for further design iterations are made.

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- 31.10.2013 DLR Bremen, Paul Zabel, Hendrik Kolvenbach: "Evaluation criteria setup discussion"
- 04.11.2013 DLR Bremen, Paul Zabel, Hendrik Kolvenbach: "Evaluation criteria weighting discussion"
- 26.11.2013 Institute for forest genetics, Hamburg, Dr. Matthias Fladung, Rainer Ebbinghaus, Hendrik Kolvenbach

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A1 Appendix

Plant Uptake / Transpiration H_2O and CO_2

Table 4.2.8 Nominal and Highest Biomass Production, Composition, and Metabolic Products

Crop	Total Biomass (Edible + Inedible), Dry Basis [$g_{dw}/m^2 \bullet d$]		Carbon Content [%]	Metabolic Reactants and Products		
	Nominal	High		Oxygen (O_2) Production [$g/m^2 \bullet d$]	Carbon Dioxide (CO_2) Uptake [$g/m^2 \bullet d$]	Water (H_2O) Uptake / Transpiration [$kg/m^2 \bullet d$]
Cabbage	6.74	10.0	40	7.19	9.88	1.77
Carrot	14.97	16.7	41	16.36	22.50	1.77
Chard	10.77		40	11.49	15.79	1.77
Celery	11.47		40	12.24	16.83	1.24
Dry Bean	25.00		46	30.67	42.17	2.53
Green Onion	10.00		40	10.67	14.67	1.74
Lettuce	7.30	7.9	40 (1)	7.78	10.70	1.77
Mushroom						
Onion	11.25		40	12.00	16.50	1.74
Pea	26.83		40 (3)	32.92	45.26	2.46
Peanut	22.50	36.0	60 (2)	35.84	49.28	2.77
Pepper	23.17		40	24.71	33.98	2.77
Radish	11.00		40 (2)	11.86	16.31	1.77
Red Beet	10.00		41	7.11	9.77	1.77
Rice	30.23	39.0	45 (2)	36.55	50.26	3.43
Snap Bean	29.70		46	36.43	50.09	2.46
Soybean	11.34	20.0	46 (1)	13.91	19.13	2.88
Spinach	7.30		40	7.78	10.70	1.77
Strawberry	22.25		43 (2)	25.32	34.82	2.22
Sweet Potato	37.50	51.3	41 (2)	41.12	56.54	2.88
Tomato	23.17	37.8	43 (2)	26.36	36.24	2.77
Wheat	50.00	150.0	42 (1)	56.00	77.00	11.79
White Potato	30.08	50.0	41 (1)	32.23	45.23	2.88

References

Information from Drysdale (2001) except as noted.
(1) Wheeler, et al. (1995)
(2) Calculated
(3) Orcun and Wheeler (2003)

Source: Hanford 2006

Market research of commercial available dehumidifiers

Market research dehumidifier						
Removed water per day	**Power consumption**	**Air flow rate**	**Brand**	**Name:**	**net price**	**brutto price**
kg/d (30 °C, 80%)	kW	m^3/h			€	€
30	0,51	n.a.	Kaut	3025	3140,00	3736,60
42	1	n.a.	Air-Dry	Ra 2101 CF	2490,00	2963,10
42	0,9	500	Zodiac	DT850	1850,00	2201,50
45	1	500	Kunz	KT-20	4200,00	4998,00
47	n.a	n.a.	Microwell	DRY 300	2070,00	2463,30
49	1,2	450	Axair	SBA 50	2930,00	3486,70
50	0,72	n.a.	Dantherm	CDP 35	2225,00	2647,75
52	1,24	n.a.	Kaut	5010	3410,00	4057,90
55	1,34	n.a.	Air-Dry	Ra 3147 CF	2980,00	3546,20
55	0,99	600	Zodiac	Sirocco 55	2750,00	3272,50
58	0,98	n.a.	Kaut	5025	4310,00	5128,90
69	1,05	n.a.	Dantherm	CDP 45	2564,00	3051,16
70	1,41	800	Kunz	KT-35	4490,00	5343,10
72	1,26	1000	Amcor	D1100	2670,00	3177,30
74	2,45	n.a.	Air-Dry	Ra 3181 CF	3390,00	4034,10
77	1,5	700	Axair	SBA 75	3435,00	4087,65
80	1,1	800	Zodiac	Sirocco 80	3190,00	3796,10
86	1,5	n.a.	Kaut	7010	5430,00	6461,70
87	1,3	1300	Amcor	DSR12	2390,00	2844,10
100	2,7	n.a.	Air-Dry	Ra 2261 CF	4180,00	4974,20
100	1,35	n.a.	Dantherm	CDP 65	3368,00	4007,92
101	n.a	n.a.	Microwell	DRY 500	3050,00	3629,50
104	1,8	700	Axair	SBA 100	3945,00	4694,55
108	2,4	1100	Kunz	KT-45	5650,00	6723,50
110	1,34	1000	Zodiac	Sirocco 100	3650,00	4343,50
135	n.a	n.a.	Microwell	DRY 800	3390,00	4034,10
145	2,6	1500	Amcor	DSR20	2570,00	3058,30
151	2,9	1000	Axair	SBA 150	4490,00	5343,10

Source: http://www.rauschenbach.de/feuchtairdry.htm

Heat transfer coefficient table

		Wärmeübergangskoeffizient α (W/(m²*K))
Wasser - Luft	Windstille	7
Wasser - Luft	Mittlerer Wind	25
Luft senkrecht zur Metallwand	ruhend	3,5...35
Luft senkrecht zur Metallwand	mäßig bewegt	23...70
Luft senkrecht zur Metallwand	kräftig bewegt	58...290
Luft längs zu ebener Wand	polierte Oberfläche v < 5 m/s	5,6 + 4 * v
Luft längs zu ebener Wand	polierte Oberfläche v > 5 m/s	$7{,}12 * v^{0{,}78}$
Luft längs zu ebener Wand	Stahlwand v < 5 m/s	5,8 + 4 * v
Luft längs zu ebener Wand	Stahlwand v > 5 m/s	$7{,}14 * v^{0{,}78}$
Luft senkrecht zur Wand im Gebäude	laminare freie Konvektion	$1{,}32 * (\Delta T / H)^{0{,}25}$
Luft senkrecht zur Wand im Gebäude	turbulente freie Konvektion	$1{,}74 * \Delta T^{0{,}33}$
Luft senkrecht zur Wand außerhalb des Gebäudes	laminarer Luftstrom	$3{,}96 * (v / L)^{0{,}5}$ wenn v * L < 8 m²/s
Luft senkrecht zur Wand außerhalb des Gebäudes	turbulenter Luftstrom	$5{,}76 * (v^4 / L)^{0{,}2}$ wenn v * L > 8 m²/s
Luft längs zur Wand inner- u. außerhalb von Gebäuden [1]	laminare Luftströmung	$3{,}9 * (v / L)^{0{,}5}$ wenn v * L < 8 m²/s
Luft längs zur Wand inner- u. außerhalb von Gebäuden [1]	turbulente Luftströmung	$11 / L + 5{,}8 * [(L * v - 8) / (L * v)] * (v^4 / L)^{0{,}2}$ wenn v * L > 8 m²/s

Source: DIN EN ISO 6946 / VDI 2055

Wärmeübergangskoeffizienten:

http://www.schweizer-fn.de/stoff/wuebergang_gase/wuebergang_gase.php (14.12.2013)

Volumetric CO_2 rating

Bezugsgröße		techn.-CO_2 kg	Erdgas L m^3	Erdgas H m^3	Propan kg	Butan kg
Brennwert H_S	(kW h)	–	10,16	11,48	13,98	13,75
Abgasvolumen V_{tr}	(m^3)	–	8,00	8,90	10,84	10,50
CO_2-Gehalt	(%)	fast 100 %	11,9	12,0	13,8	14,1
CO_2-Volumen V_{CO2}	(m^3)	0,54	0,952	1,068	1,496	1,481
CO_2-Masse je Bezugsgröße	(kg)	–	1,88	2,11	2,96	2,93
CO_2-Masse je kW h H_S	(kg)		0,185	0,184	0,212	0,213

Basisdaten zur CO_2-Produktion bei der Verbrennung verschiedener Gase

spezifisches Gewicht CO_2 = 1,977 kg/m^3

1 kWh Erdgas ergibt 0,185 kg CO_2 = 0,952 m^3
1 m^3 Erdgas-L ergibt 1,88 kg CO_2
1 m^3 Erdgas-H ergibt 2,11 kg CO_2

1 kWh Propan ergibt 0,212 kg CO_2 = 1,496 m^3
1 kg Propan ergibt 2,96 kg CO_2

Source: Täschner 2009

Filter groups and typical applications

The filter group	**The level of filtra-tion**	**The examples of separated particles material**	**Recommendation for application of air filters**
G **Filters for coarse dust particles** Efficient for particles ≥ 10 µm ***EN 779***	**G1** **G2**	• Leaves • Insects • Textile fibres • Sand • Flying ash • Mist • Hair	Only for simplest application (e.g. protection against in-sects)
	G3 **G4**	• Flower pollen • Pollen • Fog	• Waste air of painting boxes and kitchens • Protection against the pollution of air conditioning and compact instruments (e.g. window air condi-tioning, fans) • Pre - filters for the filtration classes F7 and F8(it is necessary only for heavy polluted input air) • Pre filters and circulation filters for public protec-tion equipments
F **Filters for fine dust.**	**M5**	• Spore • Cement dust • Particles creating stain or dust sediment-ation	• Entering filters for the areas with low demand(e.g. workshops,storages,garage) • Pre-filters for the filtration class F8 and F9.

Efficient for particals ≥ 1 µm ***EN 779***	**M6**	• Bacterium • Embryo on the carrying parts	• The entering filters for the area with low demand(e.g. selling areas,specific production area) • Pre-filters for the class filtration F9 and E10 • Filters for waste air for heat exchanger and recuparator
	F7 **F8**	• Acumulated carbon black • So called dust going through lung	• Circulating filters in air conditioning • End filters in air conditioning pro average request e.g. shops, offices and specific production areas. • Pre filters for the filtration class E11 and E12.
	F8 **F9**	• Tobacco smoke (roase fractions) • Metal oxide smoke(soarse fractions) • Oil smoke	• The end filters in air conditioning for higher requests e.g. offices, workshops, telecommunication centres, laboratories etc. • Outside air equipments in hospitals • Digital phone exchanges • Pre-filters for the filtration class H13 and H14 • Pre-filters for adsorbable filters(e.g. filters with active carbon) • Pre-filters in pharmacy
H **Filters for micro particles.** Efficient for particles ≥ 0,01 µm ***EN 1822***	**E10** **E11**	• Embryos • Tobacco smoke • Smoke of metal oxide • Swirl on th carrying particles • Carbon black	• End filters for the area with high request (e.g. laboratories and hospitals) • End filters for "clean areas", classes ≥ ISO 7 in pharmacy, food, optitions and light industry
	E12 **H13**	• Oil smoke in the initial stage • Aerosol micro particles • Radioactive aerosol	• End filters for hospitals with higher requirements but without any prescription for leakeage test • End filters for food. electronic, pharmacy and foil industry • Filters for waste air in nuclear technics • End filters for "clean area" classes ≥ ISO 5 • The end filters in public protection equipments
	H14	• Aerosol micro particles • Swirl	• The end filters for "clean areas" classes ≥ ISO 4 • The end filters for pharmacy, hospitals with higher requirements and strongest rules for the leakage tests
U **Filters for micro particles** ***EN 1822***	**U15** **U16** **U17**	• Aerosol micro particles	• End filters for "clean areas" classes ≥ IS0 3 • End filters for "clean areas" classes ≥ IS0 2 • End filters for "clean areas" classes ≥ IS0 1
Non Standard:			

A **Filters with active coal**	**Active coal (not impreg-nated coal)**	• Light volatile hydrocar-bon VOC'S • Asphalt, tar and petrol and kerosine fume • Solvent fume • Body civilisation and hos-pital smell • Food, kitchen and rotting smell	• Catching smell at airports, offices and public build-ings, hotels, hospitals. • Decreasing the syndrom of ill buildings • Input filtration in microelectronic • Removing the harmful gases from recirculing air
The filtration of gases	**(Impreg-nated ac-tive coal)**	• Acid spot gases • SO_2, $S0_4$, NO_2, NO_x • HCl, H_2SO_4, H_2S, HF, Cl_2	• Input filtration fot control center (e.g. at the air-port) • Input and circulating filters for eechange center in agresive conditions. • Computers area • Input and circulating filters for microelectronic
It is not standarised	**(Impreg-nated ac-tive coal)**	• Amine • NH_3, NH_4 • NMP, HMDS	• Circulating filters in microelectronics

Source: http://www.ksklimaservice.com/en/classification-of-filters-filter-properties-and-typi-cal-examples-of-use (29.01.2014)

UV Irradiation Dosage Table

Organisms:	Energy Dosage of Ultraviolet radiation (UV dose) in µWs/cm² needed for kill factor	
Bacteria	90% (1 log reduction)	99% (2 log reduction)
Bacillus anthracis - Anthrax	4,520	8,700
Bacillus anthracis spores - Anthrax spores	24,320	46,200
Bacillus magaterium sp. (spores)	2,730	5,200
Bacillus magaterium sp. (veg.)	1,300	2,500
Bacillus paratyphusus	3,200	6,100
Bacillus subtilis spores	11,600	22,000
Bacillus subtilis	5,800	11,000
Clostridium tetani	13,000	22,000
Corynebacterium diphtheriae	3,370	6,510
Ebertelia typhosa	2,140	4,100
Escherichia coli	3,000	6,600
Leptospiracanicola - infectious Jaundice	3,150	6,000
Microccocus candidus	6,050	12,300
Microccocus sphaeroides	1,000	15,400

Mycobacterium tuberculosis	6,200	10,000
Neisseria catarrhalis	4,400	8,500
Phytomonas tumefaciens	4,400	8,000
Proteus vulgaris	3,000	6,600
Pseudomonas aeruginosa	5,500	10,500
Pseudomonas fluorescens	3,500	6,600
Salmonella enteritidis	4,000	7,600
Salmonela paratyphi - Enteric fever	3,200	6,100
Salmonella typhosa - Typhoid fever	2,150	4,100
Salmonella typhimurium	8,000	15,200
Sarcina lutea	19,700	26,400
Serratia marcescens	2,420	6,160
Shigella dyseteriae - Dysentery	2,200	4,200
Shigella flexneri - Dysentery	1,700	3,400
Shigella paradysenteriae	1,680	3,400
Spirillum rubrum	4,400	6,160
Staphylococcus albus	1,840	5,720
Staphylococcus aureus	2,600	6,600
Staphylococcus hemolyticus	2,160	5,500
Staphylococcus lactis	6,150	8,800
Streptococcus viridans	2,000	3,800
Vibrio comma - Cholera	3,375	6,500
Molds	90%	99%
Aspergillius flavus	60,000	99,000
Aspergillius glaucus	44,000	88,000
Aspergillius niger	132,000	330,000
Mucor racemosus A	17,000	35,200
Mucor racemosus B	17,000	35,200
Oospora lactis	5,000	11,000
Penicillium expansum	13,000	22,000
Penicillium roqueforti	13,000	26,400
Penicillium digitatum	44,000	88,000
Rhisopus nigricans	111,000	220,000
Protozoa	90%	99%
Chlorella Vulgaris	13,000	22,000
Nematode Eggs	45,000	92,000
Paramecium	11,000	20,000
Virus	90%	99%
Bacteriopfage - E. Coli	2,600	6,600

Infectious Hepatitis	5,800	8,000
Influenza	3,400	6,600
Poliovirus - Poliomyelitis	3,150	6,600
Tobacco mosaic	240,000	440,000
Yeast	90%	99%
Brewers yeast	3,300	6,600
Common yeast cake	6,000	13,200
Saccharomyces carevisiae	6,000	13,200
Saccharomyces ellipsoideus	6,000	13,200
Saccharomyces spores	8,000	17,600

Source: http://www.americanairandwater.com/uv-facts/uv-dosage.htm (29.01.2014)

Cooling Coil Design Specifications

Hendy Coils Pty Ltd

COOLING COIL SPECIFICATIONS

Heat exchange coils used for removing heat from air in air-conditioning systems operate under very complex circumstances. However, if certain guidelines are followed trouble should not be encountered. These notes are not intended to cover the determination of duties or air volumes but rather the specifying of an economical coil after these have been established.

(1) **COIL SIZING:** The size of the face of a coil should be governed by the air volume the coil is to handle. Face velocities should be above 1.5 M/S to encourage even air distribution but below 2.6 M/S to ensure condensed water is not carried off the coil by the air stream. This figure may be exceeded if eliminators are placed downstream of the coil to catch water carried over, however air pressure drop usually becomes excessive at higher velocities. The efficiency of the coil increases with face velocity, so provided air pressure drop is within the desired limits then 2.5 M/S is most often a good figure to aim for.

Selecting a maximum face velocity will determine a minimum face size but the length to height ratio will have effect on cost. A long narrow coil has less tubes, welding and manifold than a more square coil making it cheaper to manufacture. If taken to an extreme this can result in excessive ducting costs and so a 2:1 ratio is often called for. The finned height of a cooling coil can have an effect on the performance when the coil is operating under "wet" conditions if the water running off the upper part of the coil begins to effect the air flow through the lower part. For this reason height is often limited to 750 - 900mm. If a higher coil is necessary it should be specified as 2 coils installed with a drip tray between them.

(2) **COIL LOAD:** The load or duty of the coil should be determined from heat load calculations of the space to be conditioned. The duty of the coil can be specified directly or by specifying the air off conditions required. This duty will normally have a latent heat component as well as sensible heat content. The two are added together and stated as the "Total" load and the "Sensible" load is usually specified separately. For a given duty the air off conditions can be calculated provided air volume and air on conditions are known.

The resulting air off figures tell something of the nature of the system. Very low air off temperatures indicate a low air flow or excessive duty. Representative examples would be 12 deg dry bulb and 11.5 deg Wet Bulb or lower. These conditions result in more expensive coils as the design must bring the air temperature closer to the entering cooling medium temperature. It is of course not possible to go below this temperature and very difficult to get even within a few degrees of it. On the other hand air off temperatures above 17 deg DB / 16 deg WB may indicate excessive air flow or an under estimation of load. High air off temperatures will result in cheaper coils due to greater temperature differences but care should be taken to ensure the design conditions will actually be met.

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(3) **AIR ON CONDITIONS:** The air on temperatures specified will have a big bearing on the selection of the number of rows and fin spacing for a given duty. Coil performance is determined by the temperature difference between the water and air and so the lower the air on conditions the more difficult it becomes for a coil to meet a given load. The air on humidity will also effect the total load to sensible load ratio. Specified air on should be as close as possible to normal running conditions. Higher temperatures that may exist at system start up, will increase coil performance so need not be allowed for.

Systems supplied with a mixture of fresh and return air should have the mixed air on temperature calculated using a psychometric chart. Common figures used in Melbourne are 28 Deg Celsius dry bulb and 19 deg Celsius wet bulb. Full fresh air systems are often quoted as 35DB / 21WB. If in doubt use lower dry bulb or higher wet bulbs than suspected, However keep safety margins to a minimum as the effect on cost and pressure drop can be great.

(4) **WET BULB DEPRESSION:** The difference between the air off dry bulb and wet bulb is sometimes called the wet bulb depression. Wet bulb depression is effected by the condition of the air entering the coil, the nature of the heat exchange surfaces and the temperature of that surface. When air on temperatures and total load are specified and if moisture is to be removed then only a very narrow range of control over wet bulb depression is available to the coil designer.

Wet bulb depression of the air leaving the coil usually falls between 0.1 - 2 degrees C. Wide fin spacing lowers it. The velocity of the air through the coil also has some effect. Specifying large wet bulb depression usually results in an over design in order to meet the actual sensible load rather than the specified sensible load. When really necessary large wet bulb depression can usually only be achieved with over cooling, then reheating with a separate heating coil up to the required dry bulb temperature. As a general guide, duties or air off temperatures should be specified to result in a wet bulb depression of between 0.5 and 1 degree C. The coil designer should alert you to any unusual situations past there.

(5) **WATER SUPPLY TEMPERATURES:** The water temperatures existing in a system are the other factor determining the temperature difference that drives the heat transfer of the coil and so should be accurate. Variations in the supply temperature have a large effect on the heat exchange surface required, especially when air off temperatures are low. The return water temperature and flow rate relationship also effects coil performance. High flow rates with low temperature increases result in a reduced heat transfer surface requirement in the coils, however other factors should be considered.

Increases in pipe sizes and water pressure drop increased effecting running costs may negate any savings on the coils. Lower water entering temperatures may also result in lower efficiencies in the refrigeration equipment.

The water velocity within the tubes should be kept above 0.3 M/S to ensure turbulent flow and reasonable efficiency but below 1.5 M/S to avoid erosion problem. Often there are limited choices on the available circuitry options for a given size coil and the lower limit cannot be met. The upper limit will not be exceeded if a reasonable maximum

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water pressure drop is followed so water velocities need not be of concern to the specifier. Generally water temperatures are 6 - 12 degrees or 7 - 13 degrees Celsius. Water pressure drop is often restricted to 30 - 40 kPa.

(6) **FIN SPACING:** This can be varied by the manufacturer to obtain the required thermal capacity from 236 to 551 Fins Per Meter (FPM). Close fin spacing is the most economical way to increase heat transfer performance, however the coil will collect dirt at a greater rate. Often 472 or 394 FPM are specified as a maximum to slow this process. If restricted on fin spacing and unable to satisfy a particular duty, the coil designer has no choice but to increase the face size or rows deep of the coil which can become relatively expensive. Care should be exercised in calling for less than 394 FPM unless air off temperatures are quite high. Incoming air filtration and ease of access for cleaning should also be considered in this matter.

(7) **CONSTRUCTION:** Standard coil construction is generally copper tubes with aluminum fins and galvanized steel frames. For salt air, and mid city applications, longer life can be obtained by specifying corrosion coatings, such coils are about 30% more expensive than standard construction.

Little extra cost is involved when frames are specified as aluminum and this results in one less dissimilar metal being present. Brass and Stainless Steel are also possible however cost more. Brass can lack the necessary strength in larger coils. The aluminum fins are usually the first element to fail in a coil. In a clean air situation a useful life of between 20 and 30 years is possible. Surprisingly the failure normally occurs at the fin tip rather than at the collar where it is bonded to the dissimilar copper tube, however almost all modern coils are constructed this way.

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Source: http://www.hendycoils.com.au/documents/Cooling_Coil_Design.pdf (09.12.13)

A2 Datasheets

Linde CO_2 datasheet

THE LINDE GROUP

Linde

→ Produktdatenblatt

Kohlendioxid flüssig 3.0

Reinheit in %: ≥ 99,9

Nebenbestandteile, ppm: H_2O ≤ 120

Angaben sind als ideale Volumenanteile (= Molanteile) zu verstehen

Lieferarten: **Tankwagen**

Weitere Lieferarten auf Anfrage.

Sicherheit: EG-Sicherheitsdatenblatt unter www.linde-gas.de/direkt

Umrechnungszahlen:

m³ Gas (15°C, 1 bar)	Liter flüssig (-56,6°C, 5,2 bar)	kg
1	1,569	1,848
0,637	1	1,178
0,541	0,849	1

Kennzeichnung:

Eigenschaften: tiefkalt verflüssigtes Gas, erstickend

AGW-Wert: 5000 ppm
Chemisches Zeichen: CO_2
Molare Masse: 44,01 g/mol

Tripelpunkt:

Temperatur	Druck	Schmelzwärme
216,58 K (- 56,57 °C)	5,19 bar	196,7 kJ/kg

Relative Dichte bezogen auf trockene Luft (15°C, 1 bar): 1,528
Kritische Temperatur: 304,21 K (31,06 °C)
Sublimationstemperatur bei 1,013 bar: 194,65 K (-78,5 °C)

Source: http://produkte.linde-gase.de/laserbetriebsgase/kohlendioxid_fluessig.html (20.01.2014)

Humidity/Temperature sensor: EE 160-HT3xxPBB-T004M

E+E ELEKTRONIK Ges.m.b.H. YOUR PARTNER IN SENSOR TECHNOLOGY

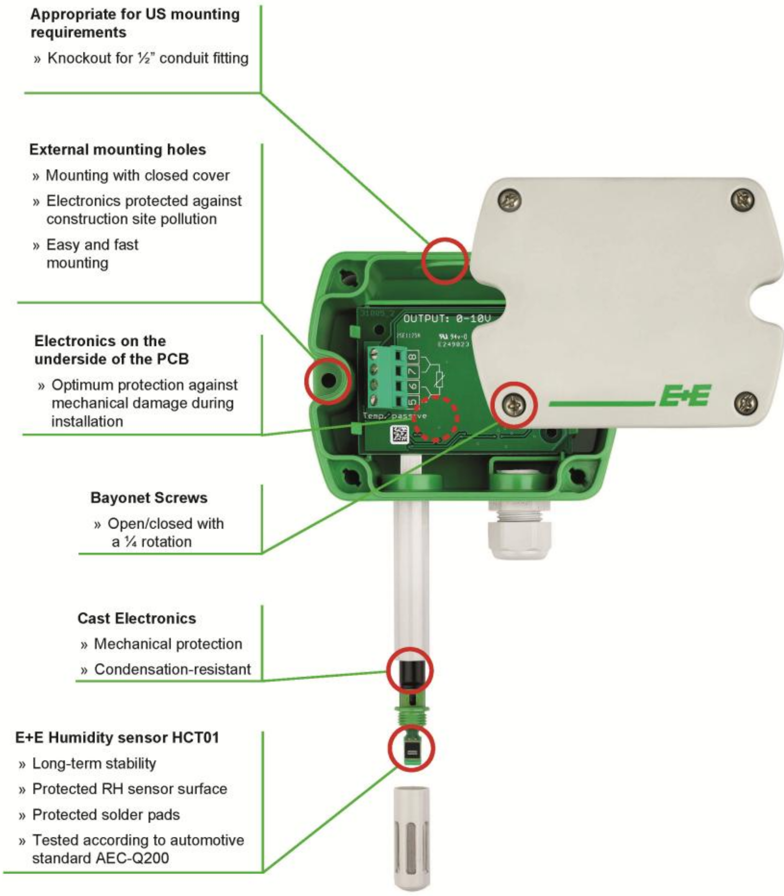
EE160

Humdity and Temperatur transmitter for HVAC Applications

Specially designed for HVAC, the EE160 sensor by E+E Elektronik is a cost-effective, highly accurate and reliable solution for measuring relative air humidity and temperature.
The enclosure minimizes installation costs and provides outstanding protection against contamination and condensation, thus ensuring flawless operation.

The EE160 employs the new humidity/temperature E+E sensor element HCT01 with excellent long term stability and resistance against pollutants. In combination with a long calibration experience, the EE160 provides a measurement accuracy of ±2.5%RH and is available for wall or duct-mounted with current, voltage or Modbus RTU output.

The configuration equipment allows user setup for the output scaling and for the interface parameters, as well as humidity and temperature adjustment of the sensor.



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Technical data

Measured values

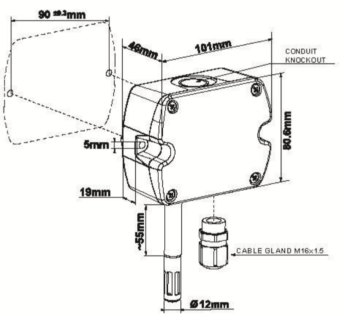
Relative Humidity		
Sensor	E+E Sensor HCT01-00D	
Analog output 0...100% RH	0-10 V	-1 mA < I_L < 1 mA oder
	4-20 mA (two-wire)	R_L < 500 Ohm
Digital output	RS485	
Working range	10...95% RH	
Accuracy at 20°C	±2.5% RH	
Temperature dependency	typ. ±0.03% RH/°C	
Temperature		
Sensor	Pt1000 (tolerance class B, DIN EN 60751)	
Analog output[1)]	0-10 V	
	4-20 mA	
Digital output	RS485	
T-Accuracy at 20°C	±0.3°C	
passive T-output	see ordering code	

General

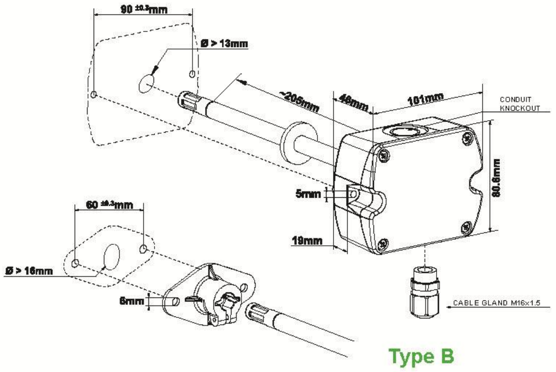
Power supply		
for 0 - 10 V / RS485	15 - 35V DC or 24V AC ±20%	
for 4 - 20 mA	10V + R_L x 20 mA < U_V < 35V DC	
Current consumption		
Analog	with DC power supplytyp. 5mA	
	with AC power supplytyp. 13mA_{eff}	
Digital	with DC power supplytyp. 15mA	
	with AC power supplytyp. 25mA_{eff}	
Connection	Screw terminals, max. 1.5 mm^2	
Housing material	Polycarbonate, UL94V-0 approved	
Protection class	IP65	
Cable gland	M16 x 1.5	
Sensor protection	membrane filter	
Electromagnetic compatibility	EN61326-1	CE
	EN61326-2-3	
Temperature ranges	Operating temperature:	-15...60°C (5...140°F)
	Storage temperature:	-25...60°C (-13...140°F)

1) Output scaling see Ordering Guide

Dimensions (mm)



Type A



Type B

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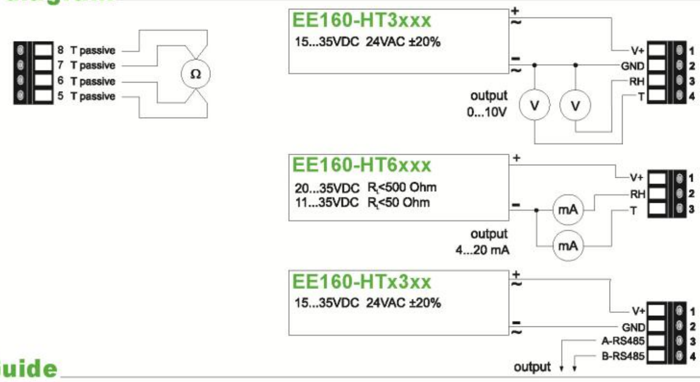
Connection diagram



Ordering Guide

Configuration

MODEL		ANALOG[1]		DIGITAL[1]		PASSIVE T-SENSOR[2]		HOUSING		TYPE		FILTER	
humidity + temperature	(HT)	0-10V	(3)	RS485	(3)	Pt 100 DIN A	(A)	polycarbonate	(P)	wall mount	(A)	membrane filter	(B)
		4-20mA	(6)	none	(x)	Pt 1000 DIN A	(C)			duct mount	(B)		
		none	(x)			NTC 10k	(E)						
						none	(x)						
EE160-													

Interface parameters - analog output

OUTPUT SCALING		SCALING[3]		UNIT	
temperature	(Tx)	°C	°F	metric	(M)
		-20...80 (024)	32...122 (076)	non-metric	(N)
		-40...60 (002)	-40...140 (083)		
		-10...50 (003)	0...140 (085)		
		0...50 (004)	20...120 (015)		

Interface parameters - digital output*

PROTOCOL		BAUDRATE		PARITY		STOPBITS		UNIT	
modbus	(1)	9600	(A)	odd	(O)	1 stopbit	(1)	metric	(M)
		19200	(B)	even	(E)	2 stopbit	(2)	non-metric	(N)
		38400	(C)	no parity	(N)				

[1] a combination of analog and digital version is not possible [2] analogue version only [3] other scaling upon request

Accessories

Configuration equipment: The configuration equipment allows user setup for the output scaling and for the interface parameters, as well as humidity and temperature adjustment of the sensor.

Position 1:
- configuration adapter (incl. USB cable for PC) HA011050

Position 2:
- for EE160 analog: cable for configuration adapter HA011059
- for EE160 digital: cable for configuration adapter HA011055

Position 3:
- configuration software: free of charge; download: www.epluse.com/EE160

Position 4 - optional:
- power supply for EE160 V03

Order example

Analog output

EE160-HT6xAPAB-Tx003M

Model:	humidity + temperature transmitter
Analog output:	4-20mA
Passive T-Sensor:	Pt 100 DIN A
Housing:	polycarbonate
Type:	wall mounting
Filter:	membrane filter
Output scaling:	temperature
Scaling:	-10...50°
Unit:	metric

Digital output

EE160-HTx3xPBB-1AE1N

Model:	humidity + temperature transmitter
Digital output:	RS485
Housing:	polycarbonat
Type:	duct mounting
Filter:	membrane filter
Protocol:	Modbus
Baudrate:	9600
Parity:	even
Stopbits:	1
Unit:	non-metric

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Source: http://www.epluse.com/fileadmin/data/product/ee160/Datasheet_EE160.pdf

CO_2 sensor: EE85-5C35

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EE85

CO_2 Transmitter and Switches for Duct Mounting

Duct mounted CO_2 transmitters and switches of the EE85 series are designed for HVAC applications. The CO_2 sensing element uses the Non-Dispersive Infrared Technology (NDIR). A patented auto-calibration procedure compensates for drift caused by the aging of the sensing element and guarantees outstanding long term stability.
Installed into a duct a small flow of air will be established by convection through the probe into the transmitter housing and back into the duct. Inside the transmitter housing the air will diffuse through a membrane into the CO_2 sensing element.
The operation in closed loop air stream avoids pollution of the CO_2 sensor.
Measuring ranges of 0...2000/5000/10000ppm correspond to an analogue interface of 0 - 5/10V or 4 - 20mA. Selectively a switching output with adjustable switching point and hysteresis is available.
The instruments can be easily positioned in the duct with the standard mounting flange.

Typical Applications

building management for residental and office areas
ventilation control

Features

very simple installation
compact housing
auto-calibration
measuring ranges: 0...10000ppm
analogue or switching output

Technical Data

Measuring Values

CO_2		
Measurement principle	Non-Dispersive Infrared Technology (NDIR)	
Sensing element	E+E Dual Source Infrared System	
Measuring range	0...2000 / 5000 / 10000ppm	
Accuracy at 25°C (77°F) and 1013mbar	0...2000ppm:	< ± (50ppm +2% of measuring value)
	0...5000ppm:	< ± (50ppm +3% of measuring value)
	0...10000ppm:	< ± (100ppm +5% of measuring value)
Response time τ_{63} 1)	< 195s	
Temperature dependence	typ. 2ppm CO_2/°C	
Long term stability	typ. 20ppm / year	
Sample rate	approx. 15s	
Temperature (passive output)		
Type of T-Sensor	please see ordering guide	

Outputs 2)

Analogue Output		
0...2000 / 5000 / 10000ppm	0 - 5V	$-1mA < I_L < 1mA$
	0 - 10V	$-1mA < I_L < 1mA$
	4 - 20mA	$R_L < 500$ Ohm
Switching Output		
Max. switching voltage	50V AC / 60V DC	
Max. switching load	0.7A at 50V AC	1A at 24V DC
Min. switching load	1mA at 5V DC	
Contact material	Ag+Au clad	

General

Supply voltage	24V AC ±20%	15 - 35V DC
Current consumption	typ. 10mA + output current max. 0.5A for 0.3s	
Warm up time 3)	< 5 min	
Housing / protection class	PC / housing: IP65, probe: IP20	
Cable gland	M16 x 1.5	cable Ø 4.5 - 10 mm (0.18 - 0.39")
Electrical connection	screw terminals max. 1.5 mm² (AWG 16)	
Electromagnetic compatibility	EN61326-1 EN61326-2-3	FCC Part 15 ICES-003 ClassB
Working temperature and conditions	-20...60°C (-4...140°F)	0...95% RH (not condensating)
Storage temperature and conditions	-20...60°C (-4...140°F)	0...95% RH (not condensating)

CE

1) minimum flow speed 1m/s (200ft/min)
2) Versions with analog output can be provided with a passive temperature sensor. This is fitted in the filter cap.
3) warm up time for performance according to specification

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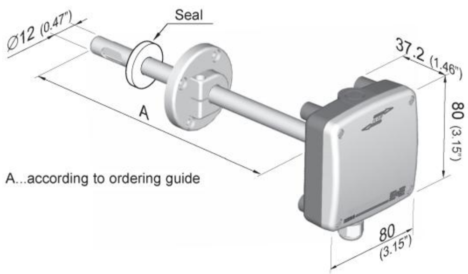
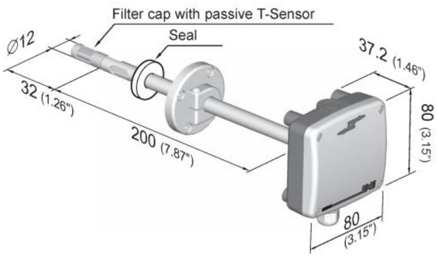
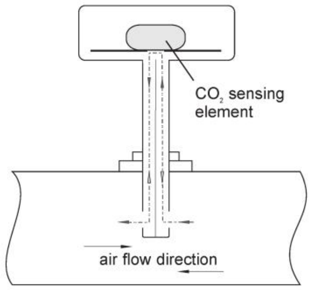
Dimensions (mm)





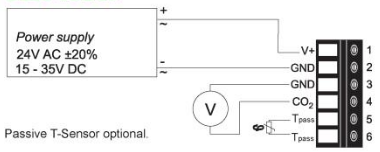
Operation Principle



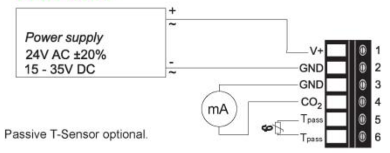
Connection Diagram

Analogue Output

EE85-xC2/3x

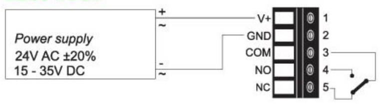


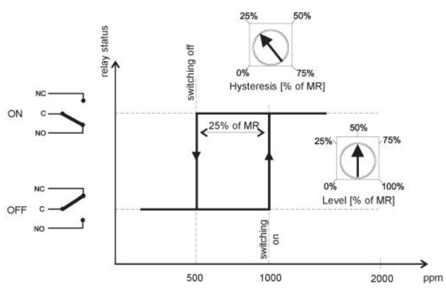
EE85-xC6x



Switching Output

EE85-xCSx





Ordering Guide

MEASURING RANGE		MODEL		OUTPUT		T-SENSOR (only passive)		PROBE LENGTH (see dimensions „A")	
0...2000ppm	(2)	CO_2	(C)	0 - 5V	(2)	Pt 100 DIN A	(A)	50mm	(2)
0...5000ppm	(5)	CO_2 + $T_{passive}$	(CP)	0 - 10V	(3)	Pt 1000 DIN A	(C)	200mm[2]	(5)
0...10000ppm	(10)			4 - 20mA	(6)				
				switching output[1]	(S)				
EE85-									

1) Switching output (S) only available for model C
2) Version CP only possible with 200mm (7.87").

Order Example

EE85-5C35

measuring range:	0...5000ppm
model:	CO_2
output:	0 - 10V
probe length:	200mm

EE85 141

Source: http://www.epluse.com/fileadmin/data/product/ee85/datasheet_EE85.pdf

Cold water supply

MPE-C: Luftgekühlte Kaltwassersätze zur Außenaufstellung

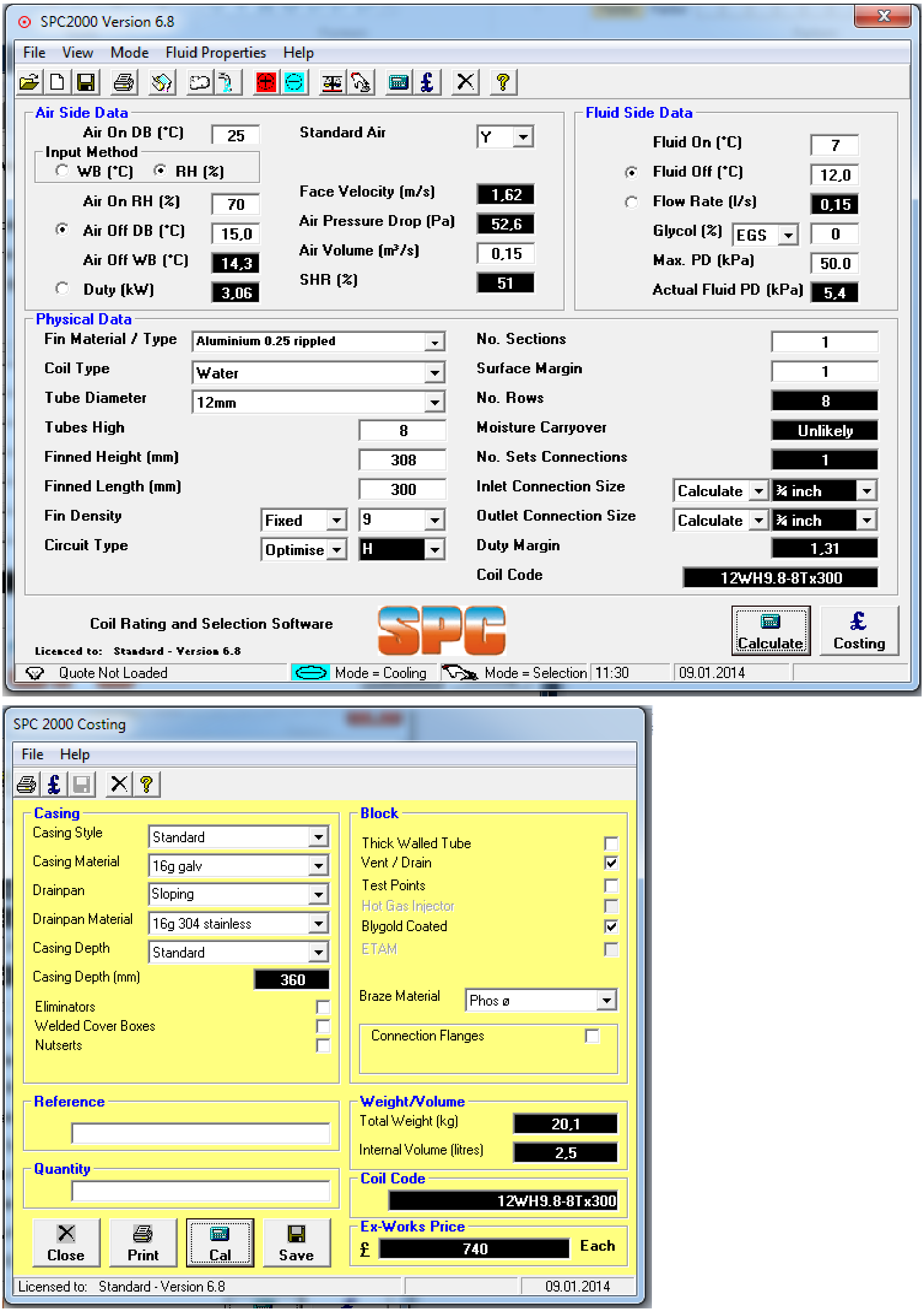
MPE..AA		004CM	005CM	007CM	008CM	008C0	010CM	010C0
Spannungsversorgung	V / Ph / Hz	230 / 1 / 50				400 / 3 / 50	230 / 1 / 50	400 / 3 / 50
Kühlleistung	kW	4,11	5,10	6,66	8,40	8,40	9,25	9,25
Leistungsaufnahme	kW	1,35	1,70	2,26	3,35	3,09	3,22	3,22
EER	kW/kW	3,06	3,01	2,95	2,51	2,72	2,87	2,87
ESEER	kW/kW	3,54	3,39	3,32	2,98	3,36	3,38	3,38
Wasservolumenstrom	m³/h	0,71	0,88	1,15	1,44	1,44	1,59	1,59
Wasserseitiger Druckverlust	kPa	2	4	6			34	
Max. Leistungsaufnahme	kW	2,0	2,3	3,0	5,0	5,0	5,1	7,2
Max. Stromaufnahme	A	9,8	11,6	15,3	24,2	9,2	26,3	14,4
Anlaufstrom	A	38	44	63	98	49	99	50
Scroll-Verdichter/ Kreisläufe	Anzahl	1 / 1						
Luftvolumenstrom	m³/h	3.635		3.406			7.385	
Durchmesser Wasseranschlüsse	Zoll	1					1 1/4	
Höhe	mm	758					1.250	
Länge	mm	960					1.220	
Tiefe	mm	450					560	
Schalldruck-/Schallleistungspegel	dB(A)	38 / 66		39 / 67			41 / 69	
Transportgewicht	kg	98	100	107	110	110	202	202
Preis	**€**	**3.939,-**	**4.052,-**	**4.277,-**	**4.840,-**	**4.840,-**	**5.447,-**	**5.447,-**

Chosen supply: MPE-C 005CM + extras

Source: Galetti catalogue 05/2013

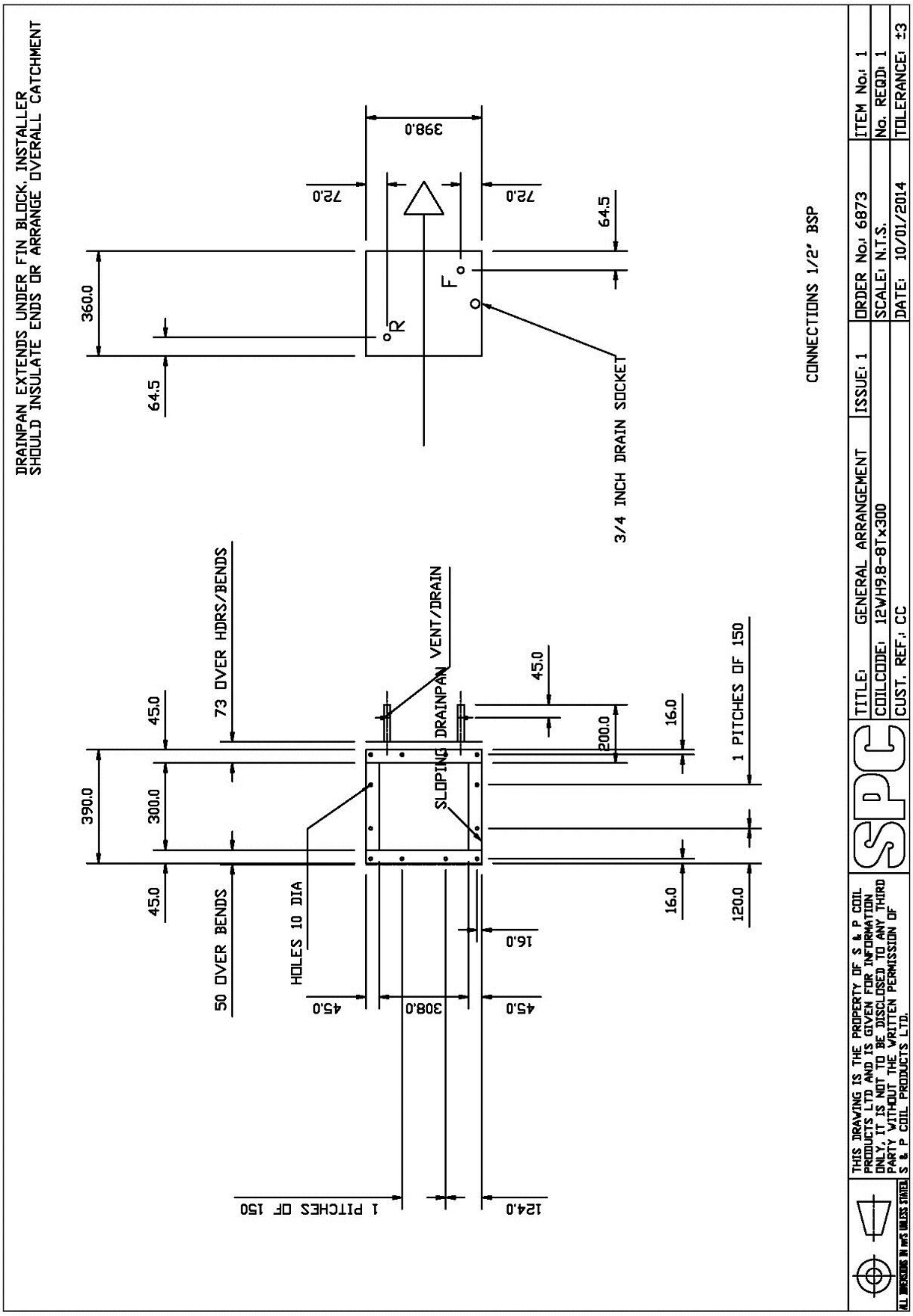
KAUT Klimatechnik

Cooling coil datasheet



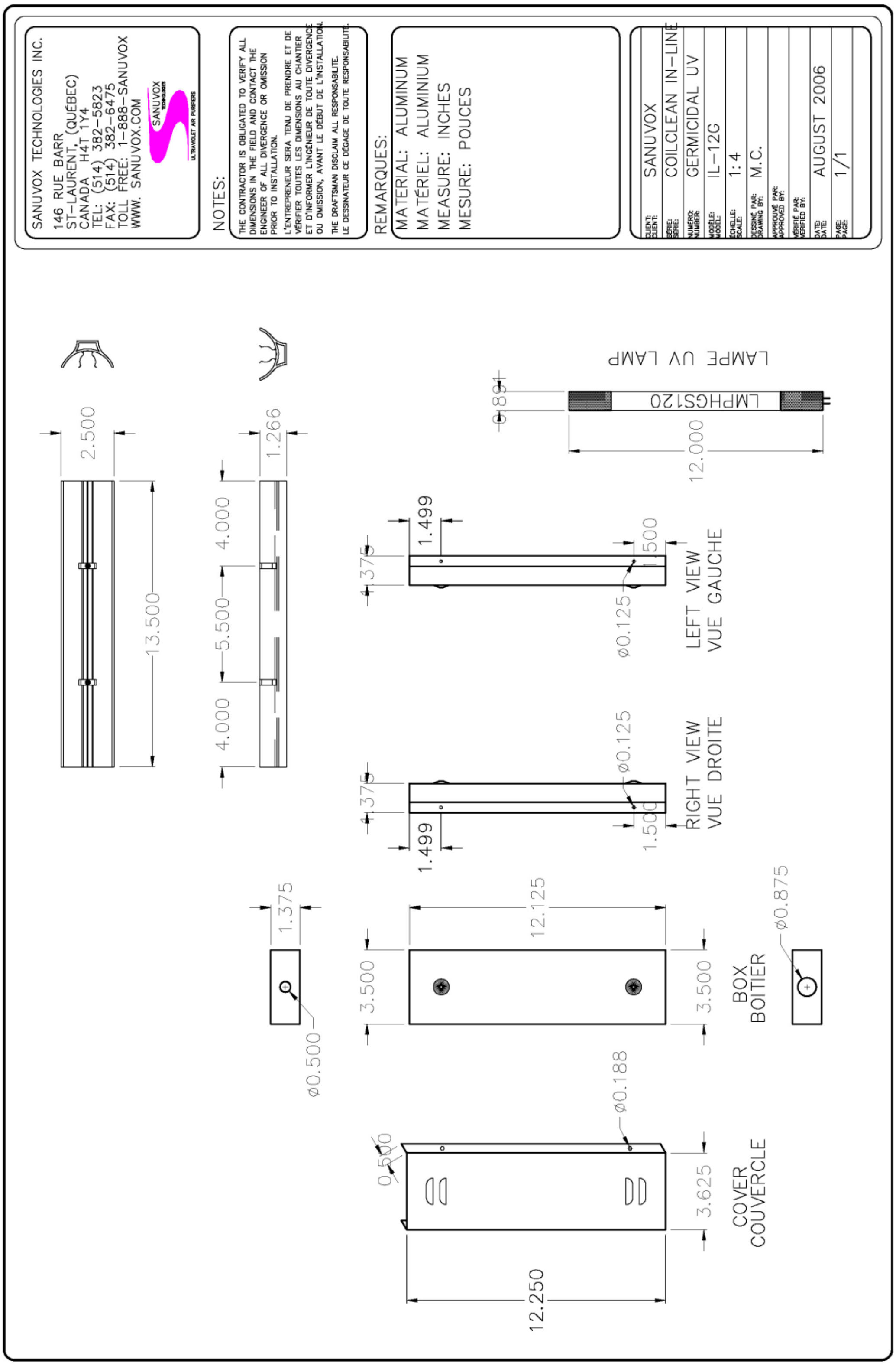
Source: SPC2000 Version 6.8. (SPC Coil Rating and Selection Software)

Cooling coil datasheet



Source: SPC Coils

UVC lamp Datasheet



Source: http://www.sanuvox.com/en/pdf/coilclean_IL_series.pdf (03.02.2014)

Sanuvox CoilClean Coil Irradiation

Note: Results are as at lamp Burn-In time 100 Operating Hours

REFERENCE: 0

Installation

Coil Width	300 mm	Lamp Position on Coil*	UPSTREAM
Coil Height	30.8 cm	*Lamp Cooling Effects will occur on a Downstream Installation	
Distance between lamp and coil	100 mm	Lamp Fouling*	NO FOULING
		*Lamp Fouling will occur on a Downstream Installation	
Lamp Length	12 in		
Number of Rows	1	Total number of lamps and fixtures required	1
Number of Lamps per Row	1	Total Input Power Required	18 W

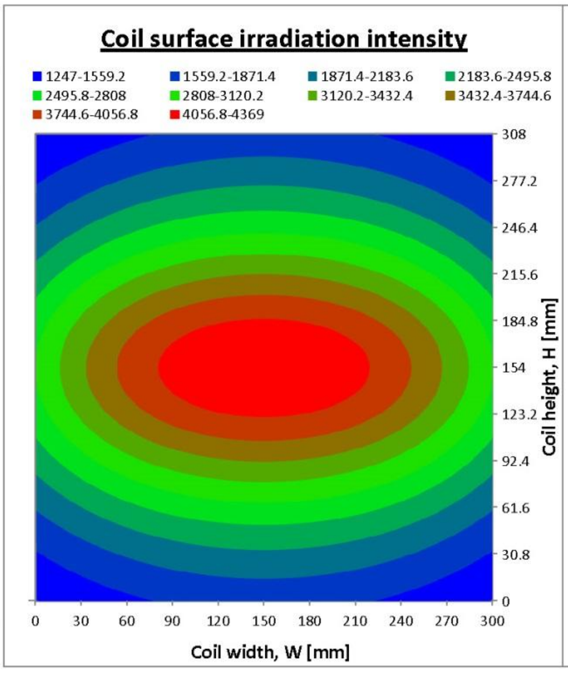
Coil surface UV Irradiation Intensity

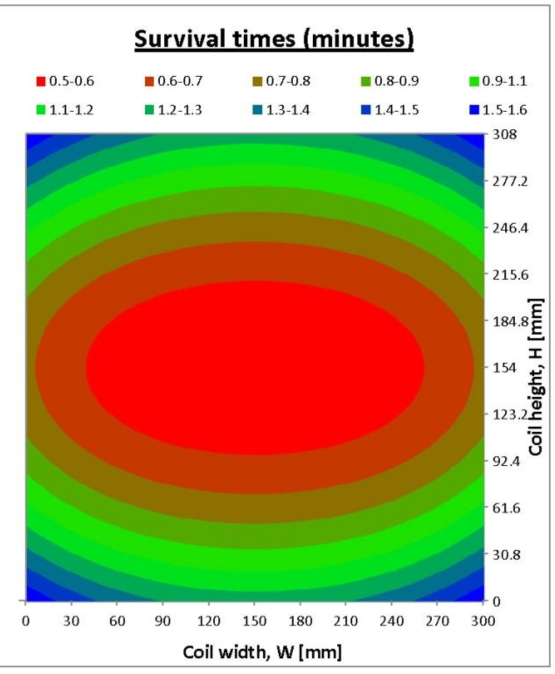
Minimum UV Irradiation Intensity	1247 $\mu W/cm^2$
Average UV Irradiation Intensity	2712 $\mu W/cm^2$
Maximum UV Irradiation Intensity	4368 $\mu W/cm^2$

Survival time of BACILLUS CEREUS SPORES

with disinfection rate of 99.9 %

Maximum survival Time	2 min
Average Survival Time	1 min
Minimum Survival Time	0 min





Sanuvox Technologies Inc 07/02/2014 Report

Sanuvox CoilClean Coil Irradiation

Note: Results are as at lampBurn-In 100 Operating Hours

REFERENCE:

Input parameters

Dimensions

	English unit		Metric unit	
Coil Width	300	mm	0.3	m
Coil Height	308	mm	0.308	m
Distance between lamp and coil	100	mm	0.1	m

Installation

Number of rows	1	
Row		
1	0.154	m
2	#N/A	m
3	#N/A	m
4	#N/A	m
5	#N/A	m
6	#N/A	m

Lamps per row	1	**CAUTION!!! Lamp Length exceeds Coil Width.**
Column		
1	#N/A	m
2	#N/A	m
3	0.00	m
4	#N/A	m
5	#N/A	m

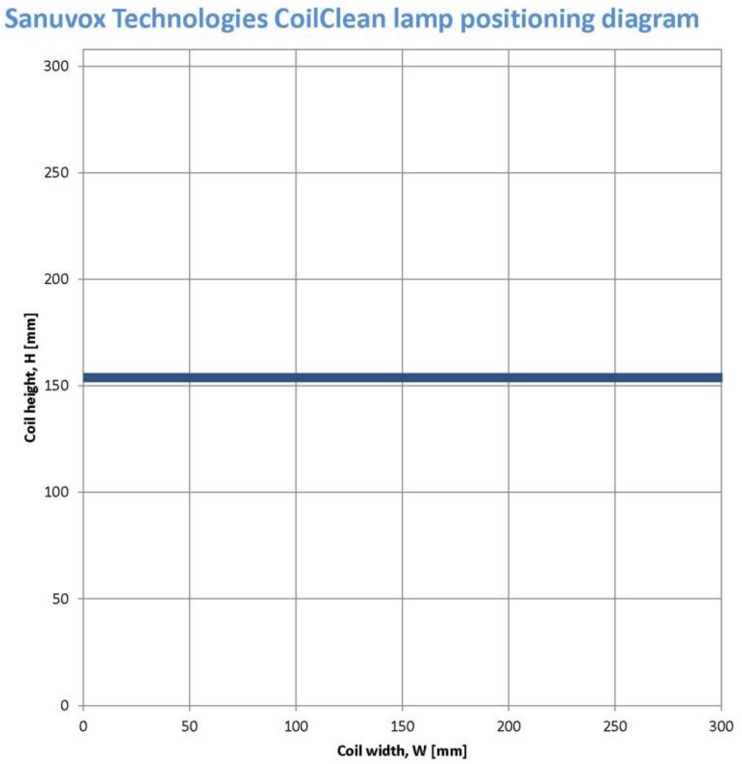
Sanuvox CoilClean model	**IL12**			
Lamp length	12	in	0.3048	m
Lamp arc length	9	in	0.2286	m
Lamp diameter	19	mm	0.019	m
Power per lamp (rated)			17.9	W
Power per length	1.5	W/in	59	W/m
Power per surface area	131.2	mW/cm^2	1312	W/m^2
UVC power per surface area	41.3	mW/cm^2	413	W/m^2
UVC efficiency			31.5	%
UVC power per lamp			5.6	W
UVC power per length			24.7	W/m

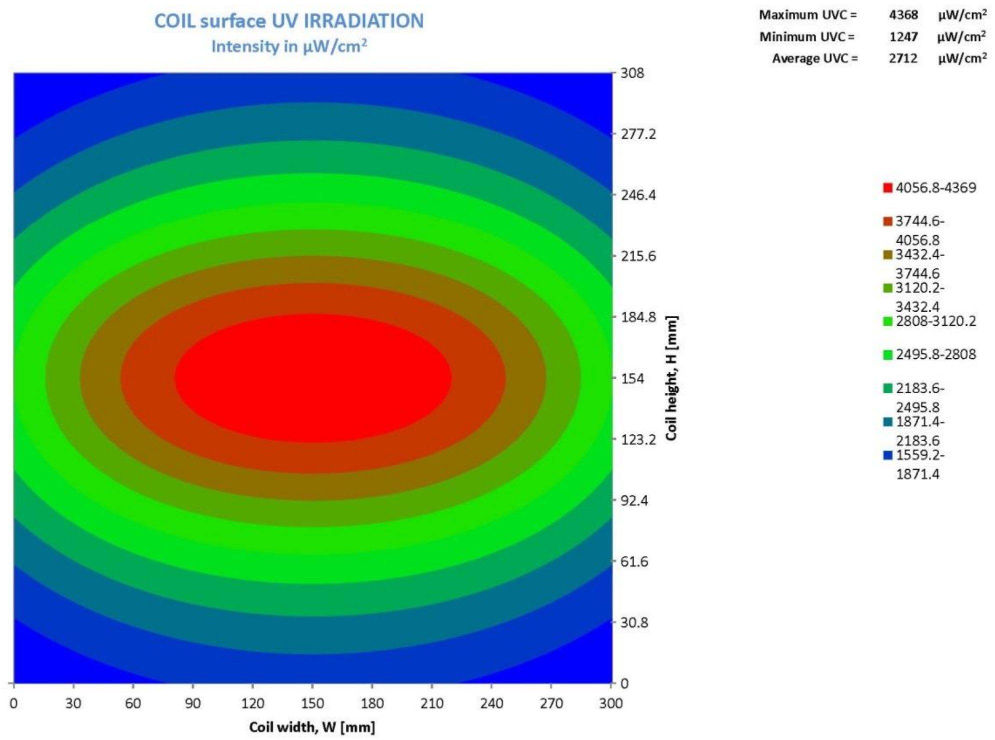
Lamp Efficiency @ 100 Hours	99.9	%	
Reflection coefficient	50	%	
Lamp position on coil	UPSTREAM		Note: Lamp Cooling Effects will occur on a Downstream Installation
Lamp fouling	NO FOULING		Note: Lamp Fouling will occur on a Downstream Installation
Required kill rate	99.9	%	
Target Contaminant	**Bacillus Cereus spores**		177.305 J/m^2

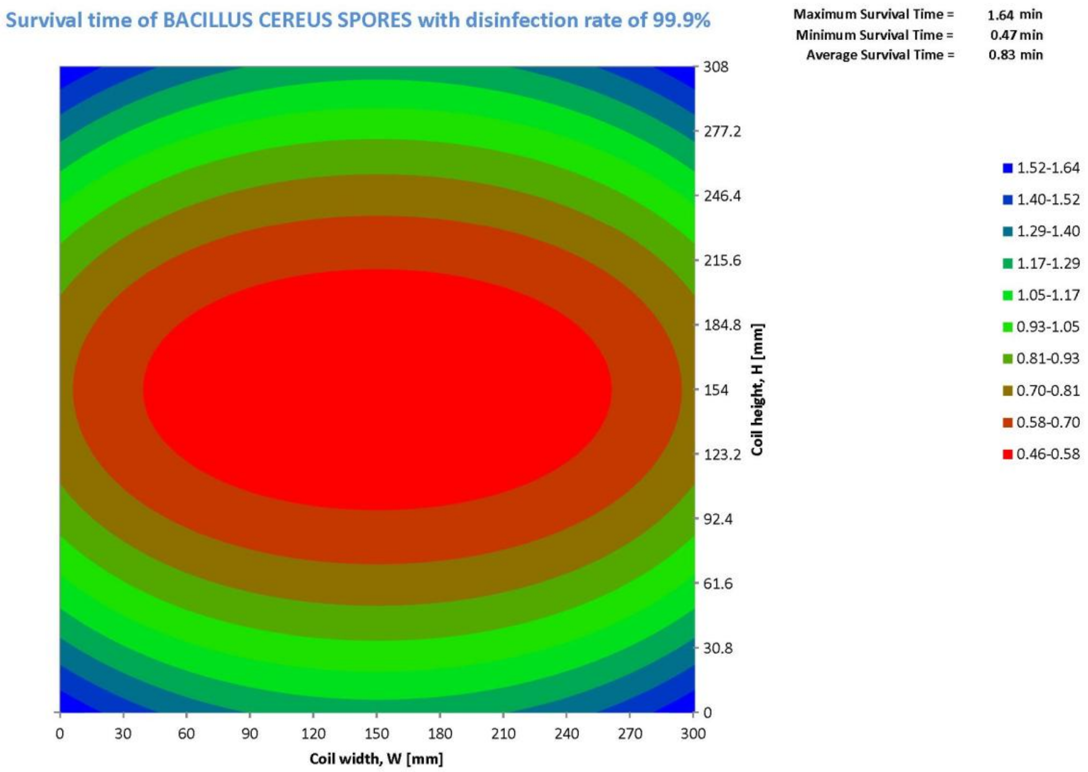
Sanuvox Technologies Inc 07/02/2014 Parameters

Sanuvox CoilClean Coil Irradiation

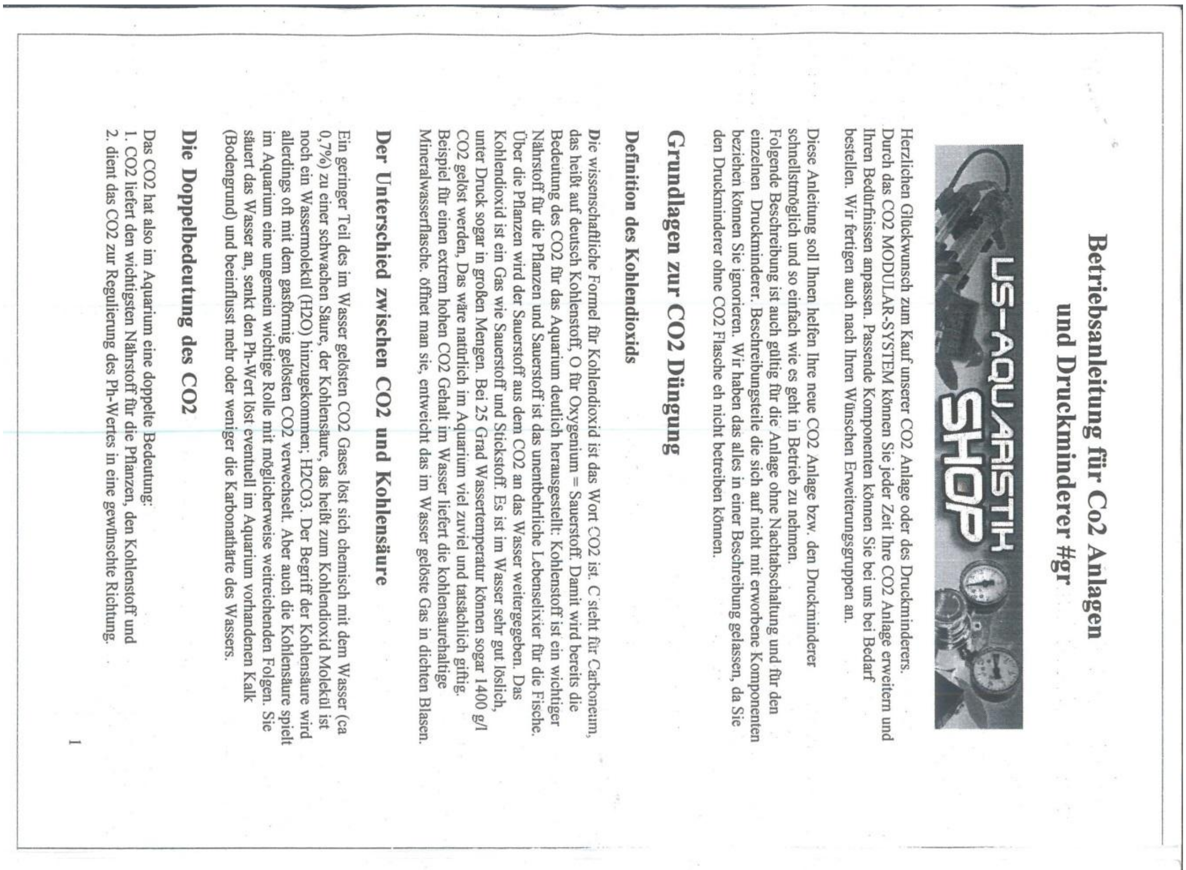
Note: Results are as at lampBurn-In 100 Operating Hours







CO_2 valve Datasheet



Betriebsanleitung für Co2 Anlagen und Druckminderer #gr

Herzlichen Glückwunsch zum Kauf unserer CO2 Anlage oder des Druckminderers. Durch das CO2 MODULAR-SYSTEM können Sie jeder Zeit Ihre CO2 Anlage erweitern und Ihren Bedürfnissen anpassen. Passende Komponenten können Sie bei uns bei Bedarf bestellen. Wir fertigen auch nach Ihren Wünschen Erweiterungsgruppen an.

Diese Anleitung soll Ihnen helfen Ihre neue CO2 Anlage bzw. den Druckminderer schnellstmöglich und so einfach wie es geht in Betrieb zu nehmen.
Folgende Beschreibung ist auch gültig für die Anlage ohne Nachtabschaltung und für den einzelnen Druckminderer. Beschreibungsteile die sich auf nicht mit erworbene Komponenten beziehen können Sie ignorieren. Wir haben das alles in einer Beschreibung gelassen, da Sie den Druckminderer ohne CO2 Flasche eh nicht betreiben können.

Grundlagen zur CO2 Düngung

Definition des Kohlendioxids

Die wissenschaftliche Formel für Kohlendioxid ist das Wort CO2 ist. C steht für Carboneum, das heißt auf deutsch Kohlenstoff, O für Oxygenium = Sauerstoff. Damit wird bereits die Bedeutung des CO2 für das Aquarium deutlich herausgestellt: Kohlenstoff ist ein wichtiger Nährstoff für die Pflanzen und Sauerstoff ist das unentbehrliche Lebenselixier für die Fische. Über die Pflanzen wird der Sauerstoff aus dem CO2 an das Wasser weitergegeben. Das Kohlendioxid ist ein Gas wie Sauerstoff und Stickstoff. Es ist im Wasser sehr gut löslich, unter Druck sogar in großen Mengen. Bei 25 Grad Wassertemperatur können sogar 1400 g/l CO2 gelöst werden, Das wäre natürlich im Aquarium viel zuviel und tatsächlich giftig. Beispiel für einen extrem hohen CO2 Gehalt im Wasser liefert die kohlensäurehaltige Mineralwasserflasche. öffnet man sie, entweicht das im Wasser gelöste Gas in dichten Blasen.

Der Unterschied zwischen CO2 und Kohlensäure

Ein geringer Teil des im Wasser gelösten CO2 Gases löst sich chemisch mit dem Wasser (ca 0,7%) zu einer schwachen Säure, der Kohlensäure, das heißt zum Kohlendioxid Molekül ist noch ein Wassermolekül (H2O) hinzugekommen; H2CO3. Der Begriff der Kohlensäure wird allerdings oft mit dem gasförmig gelösten CO2 verwechselt. Aber auch die Kohlensäure spielt im Aquarium eine ungemein wichtige Rolle mit möglicherweise weitreichenden Folgen. Sie säuert das Wasser an, senkt den Ph-Wert löst eventuell im Aquarium vorhandenen Kalk (Bodengrund) und beeinflusst mehr oder weniger die Karbonathärte des Wassers.

Die Doppelbedeutung des CO2

Das CO2 hat also im Aquarium eine doppelte Bedeutung:
1. CO2 liefert den wichtigsten Nährstoff für die Pflanzen, den Kohlenstoff und
2. dient das CO2 zur Regulierung des Ph-Wertes in eine gewünschte Richtung.

1

1. Der Kohlenstoff als Pflanzennährstoff

Der Kohlenstoff ist für die Pflanzen auf der Erde der mengenmäßig bedeutendste Nährstoff, also auch für Aquarienpflanzen. Während die Landpflanzen den Kohlenstoff aus dem Kohlenstoffdioxidgehalt der Luft aufnehmen, stehen den Wasserpflanzen theoretisch mehrere Quellen zur Verfügung. Einmal aus dem "freien" Kohlendioxid (CO2) das im Wasser gelöst ist, zum anderen aus dem flüssigen Kohlenstoff der Kohlensäure, und schließlich aus dem gebundenen in den Karbonaten. Besonders die letzte Möglichkeit, die von den Pflanzen genutzt wird, wenn kein gasförmiges CO2 vorhanden ist, hat chemische Konsequenzen. Der PH Wert des Aquarienwassers steigt dabei bis hoch ist alkalische an, je nach Pflanzenart und Gattung und je nach Lichtstärke können Werte bis zu 8 bis 9 PH entstehen. Im Aquarium ist es deshalb in jedem Falle empfehlenswert, nur die erste Möglichkeit, nämlich die des freien CO2 zu realisieren.

2. CO2 als PH Regulativ

Mit dem gasförmigen CO2 beeinflussen wir auch Karbonathärte und PH Wert. Allerdings ist dies ein sehr komplizierter Komplex. Um die im Wasser vorhandenen Karbonate in Lösung zu halten und um zu vermeiden das sie als Salze ausfallen und den PH Wert negativ verändern, ist je nach Höhe des Karbonatgehaltes eine gewisse Menge CO2 Gas im Wasser nötig. Die CO2 Tabelle (Tabelle.1) zeigt den optimalen CO2 Gehalt bei verschiedenen Karbonathärten und PH Gehalten an. Für den interessierten Leser empfehle ich entsprechende Kapitel in den Büchern "Das optimale Aquarium" und "Mein erstes Aquarium" nachzulesen. Kurz, auch der Aspekt PH Wert und Karbonathärte fordert eine gute CO2 Versorgung im Aquarium.

Resumee

Pflanzenvielfalt im Aquarium ist nur mit einer gut funktionierenden CO2 Düngung möglich. Die verschiedenen Pflanzenarten sind nämlich ungleich befähigt, ihren Kohlenstoffbedarf aus den verschiedensten Kohlenstoffquellen zu decken. Einige Pflanzenarten sind immer anderen überlegen, vor allem in der relativen Enge eines Aquariums. Nach kurzer Zeit können ohne künstliche CO2 Zufuhr nur noch diejenigen Pflanzen überleben, die auch die Kohlenstoffquellen in den Karbonaten nutzen können, die aber nur schwer zu erschließen sind und nur von solchen Pflanzen die es gelernt haben, im Wasser mit hohen PH Werten zu leben. Dieser Konkurrenzkampf um den Kohlenstoff verändert in dem kleinen Volumen eines Aquariums das chemische Milieu gleichermaßen negativ für Fische und für viele Pflanzen. Dies ist die Erklärung dafür, wenn wir im Aquarium ohne CO2 Düngung keine Pflanzenvielfalt erreichen können.

2

Aufbau und Funktion des Druckminderers

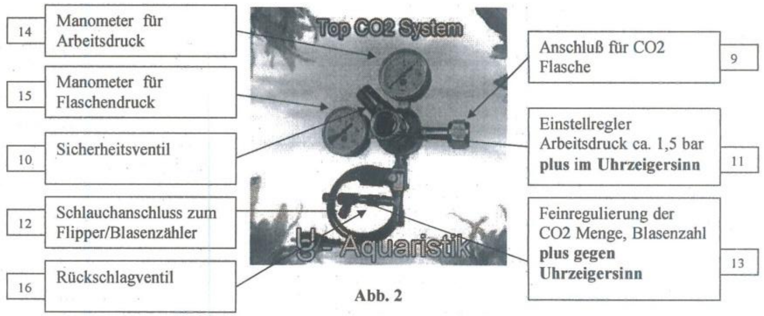


Abb. 2

Installation

1. Packen Sie alle Komponenten aus und kontrollieren Sie die Vollständigkeit.

2. Stellen Sie die CO2 Flasche auf eine feste Unterlage(Fußboden).

3. Montieren Sie die Baugruppe Druckregler, mit dem Anschluss(9) an die Flasche mittels Überwurfmutter anschrauben und festziehen mit dem mitgelieferten Schlüssel. Bei unseren Systemen wird der Schlüssel immer mitgeliefert. Bitte richtig fest ziehen, keine Angst da bricht nichts ab.

Bitte unbedingt auf Dichtheit prüfen!! Etwas Wasser in einen Becher und 3-4 Tropfen Spülmittel dazu. Das ganze umrühren und mit einem kleinen Pinsel die komplette Verbindungsstelle der Flasche mit dem Druckregler ab pinseln. Wenn die Flasche anderen Tag leer ist lag es zu 99% daran, dass es nicht richtig dran war. In diesem Fall können wir die Flasche nicht auf Garantie tauschen.

Wenn Sie ganz sicher sein wollen, folgende Methode verwenden: Flasche auf-Arbeitsdruck auf 2 bar-Nadelventil zu-Nachtabschaltung anstecken-jetzt Flasche wieder zu drehen. Der Druck ist jetzt nur im Regler, wenn was undicht ist, ist nicht die Flasche leer sondern nur das Volumen vom Regler. Der Druck muss normal ewig so stehen bleiben. Ca. 8 Stunden reichen aber zum Test aus. Wenn der Druck gesunken ist, ist die Verschraubung nicht fest genug.

Falls Sie Fragen haben stehen wir Ihnen gerne zur Verfügung.

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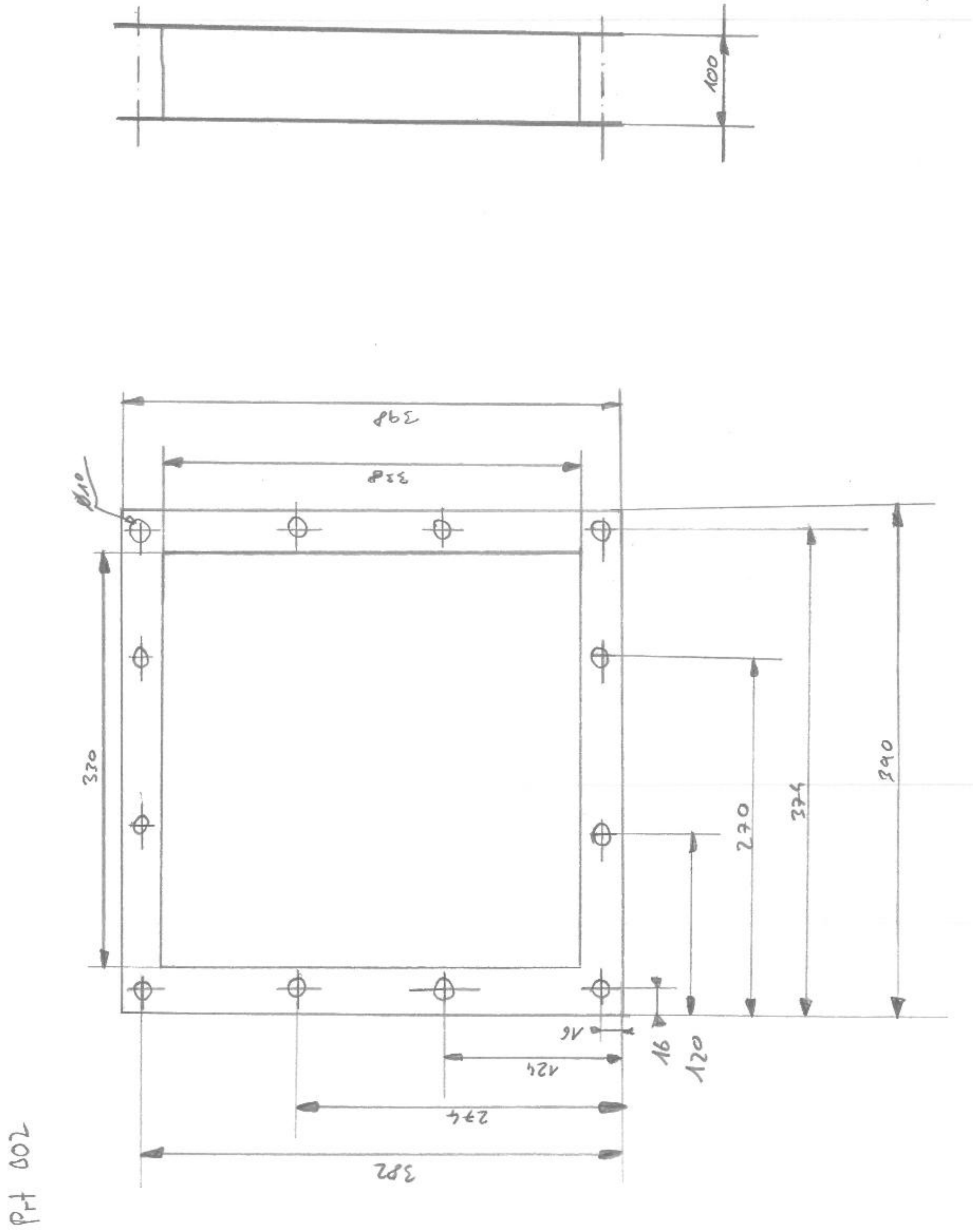
3

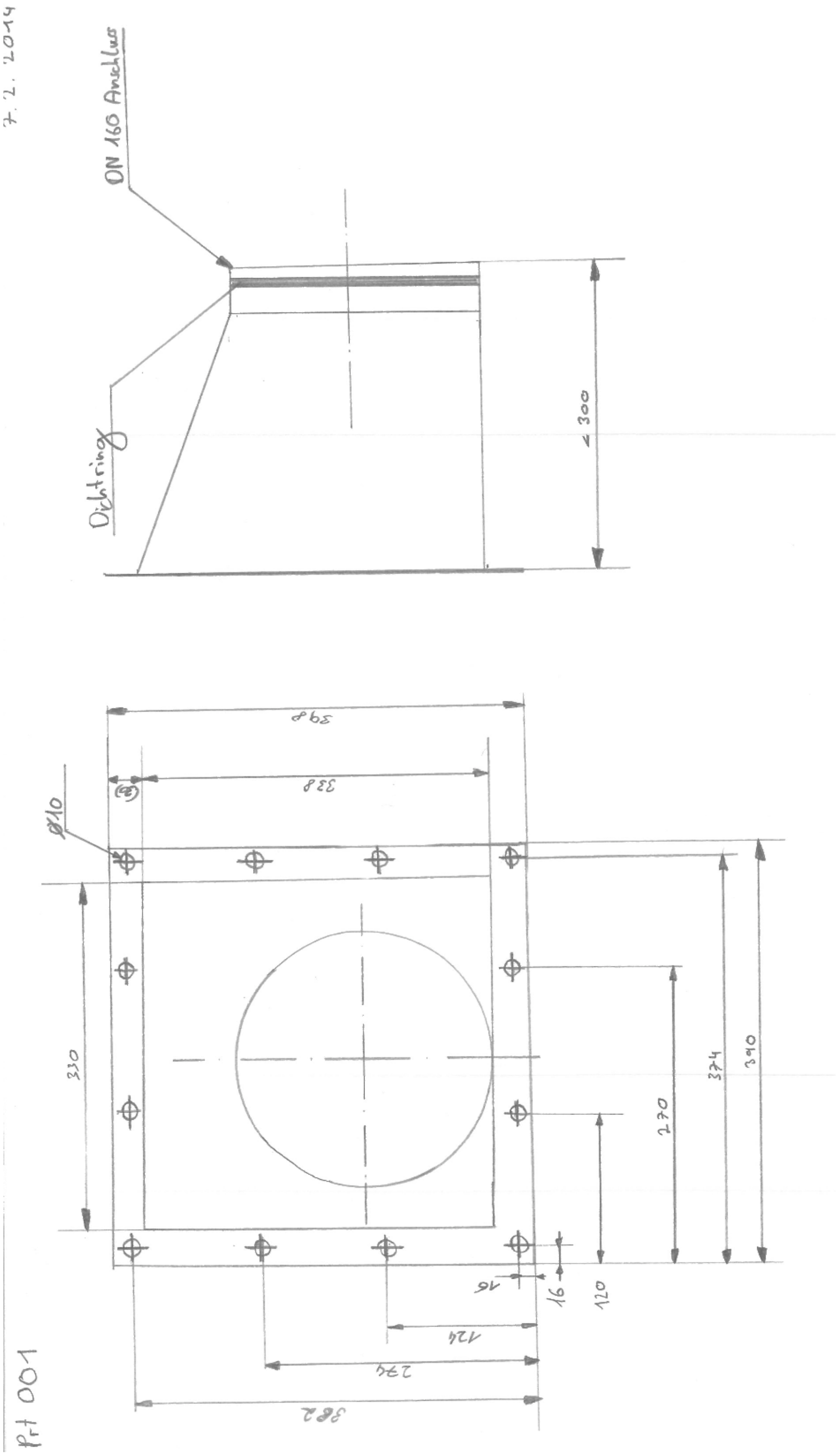
Source: US-Aquaristik Shop

A3 Manufacturing drawings

Housing for UVC lamp



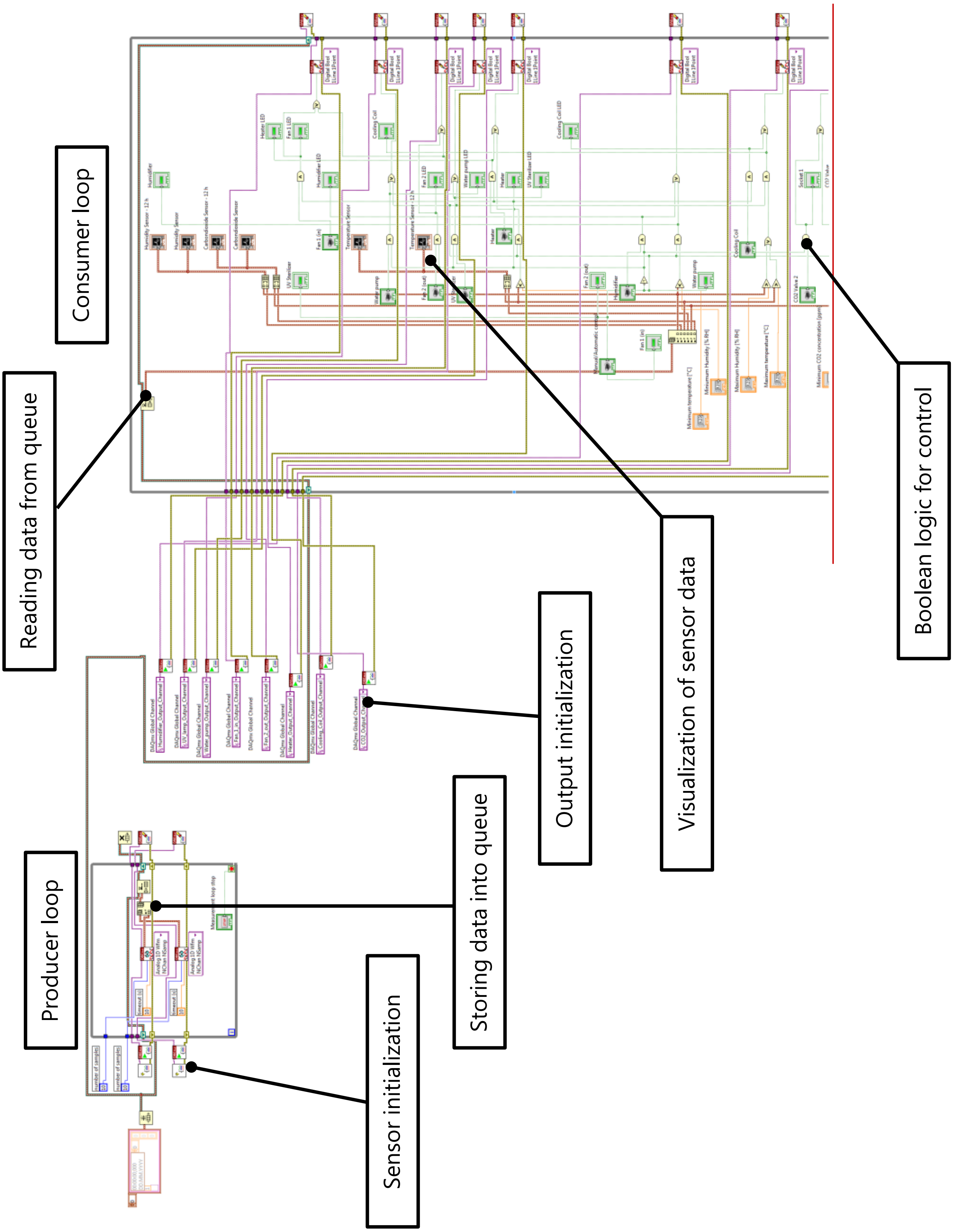
Connector to integrate cooling coil in DN 160 mm air ducts


DN 160 Anschluss
Dichtring
598
338
Ø10
330
270
374
390
16
120
124
274
382

A4 Software description

The LabVIEW program consists of two while loops. This construction is known as a producer/consumer structure and is most efficient if large amount of data is handled. In the producer loop, the sensor data is read continuously and queues into an array. The items are read in the consumer loop under the FIFO principle and continuously monitored on charts. If the manual/automatic switch is set to automatic, the measured values are compared with the boundary conditions entered in the graphical user interface. Boolean logic is used for this part of the source. Depending on the status of the comparison an output is changed to high, which leads to a switched-on relay and hence an activated device in the AMS. However, if the switch between automatic and manual control is set to manual, the automatic control stops and only manual control of the devices is possible.

The sensors are configured in the LabVIEW device manager. Since the sensor data output is analog voltage per default, a linear fitting to the actual measurement scale was necessary.


Consumer loop
Reading data from queue
Boolean logic for control
Visualization of sensor data
Output initialization
Storing data into queue
Producer loop
Sensor initialization

Eidesstaatliche Erklärung

Hiermit erkläre ich, dass ich die vorgelegte Arbeit einschließlich aller beigefügter Materialien selbständig verfasst und keine anderen als im Literaturverzeichnis angegebenen Quellen benutzt habe. Dies gilt für alle Quelltypen.

Ich habe alle Passagen und Sätze der Arbeit, die wortwörtlich oder sinngemäß anderen veröffentlichten und nicht veröffentlichten Werken entnommen sind, in jedem einzelnen Fall unter genauer Angabe der Herkunft der Quelle deutlich als Entlehnung gekennzeichnet.

Die Arbeit ist in gleicher oder ähnlicher Form noch nicht eingereicht worden.

Mir ist bekannt, dass Zuwiderhandlungen gegen diese Erklärung und bewusste Täuschungen die Benotung der Arbeit mit der Note 5.0 zur Folge haben kann.

Ort/Datum Unterschrift